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ENERGY INNOVATIONS SMALL GRANT PROGRAM: 2002 INDEPENDENT ASSESSMENT REPORTS

PIER FINAL PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions. PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

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For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Abstract

The Energy Innovation Small Grants (EISG) program is specifically designed for higher risk, “proof-of-concept” ideas, in which the Energy Commission explicitly tracks—and expects—a number of technical failures. As a “proof-of-concept” program, EISG seeks out concepts that are not yet proven and are very early in the research pipeline. These programs encourage technical innovation and risk-taking. In 2002, the Energy Commission awarded up to \$75,000 for EISG grants to test a new idea. After project completion, the Public Interest Energy Research Program uses independent experts to evaluate the research results and assess the technical success compared to the original project objectives, as well as the likelihood the product will succeed in the market.

Independent assessment reports are written at the completion of every EISG grant projects. The report outlines the objectives of the project, highlights the successes and failures, and offers recommendations for potential future work. This summary report includes many of the independent assessment reports for EISG grant projects awarded during 2002.

Keywords: EISG, Independent Assessment Report, electricity, natural gas, research, project, market, objectives, summary, highlights, outcomes, conclusions, benefits

Executive Summary

The Energy Innovations Small Grant (EISG) program is a component of the Public Interest Energy Research (PIER) Program that is managed by the California Energy Commission. The PIER Program benefits California electric and gas ratepayers by funding energy research, development, and demonstration (RD&D) projects that are not adequately provided for by the competitive and regulated energy markets.

The Commission recognizes the need for a program to support the early development of promising new energy technology concepts, a niche not covered by PIER general solicitations that focus primarily on development of established concepts. The Commission established the EISG program to meet this need. In addition, to encourage participation in the program, the process for soliciting, evaluating, and awarding grants has been simplified and streamlined. This report includes project assessment reports for grant projects that were awarded in 2002 and have not been previously published.

All data sources for tables and figures are from the author unless otherwise noted.

1.0 Introduction

In 2002, the Energy Innovations Small Grant (EISG) program funded 25 grant projects for a total of \$1.9 million. This report contains the IARs (Independent Assessment Reports) from 2002 EISG projects that have yet to be published. (See Table 1 below.)

Table 1. 2002 EISG Projects

Project	Researcher	EISG Funding
Sealing and Contacting to Novel Integrated Solid Oxide Fuel Cells	Northwestern University	\$75 K
Low Cost, Energy Saving Motor Controller for Residential and Industrial Buildings	The Board of Trustees of the University of Illinois	\$70 K
Detecting Optimal Fan Pressure	Federspiel Controls	\$75 K
Fault Location Techniques for Distribution Feeders Containing Distributed Generation	Clemson University	\$75 K
Steady State Security Assessment of Deregulated Power Systems	Clemson University	\$75 K
High Efficiency Organic Thin Film Solar Cell	Interphases Research	\$75 K
Unified Power Quality Conditioner Using One-Cycle Control	University of California, Irvine	\$75 K
Methane Sensor for Control and Automation	Carthago International Solutions, Inc.	\$75 K
Instant Snap-In Load Shed Device for Incandescent Lighting	Rensselaer Polytechnic Institute	\$75 K
Novel Approaches to Ignition Enhancement of Natural Gas Under Engine-Like Conditions	University of Southern California	\$75 K
A Dynamic Ceiling For Improved Comfort With Evaporative Cooling	Steve Winter Associates, Inc.	\$75 K
Integrating Evaporative Cooling With Dynamic Insulation for Occupant Thermal Comfort	Thermochem, Inc.	\$75 K

Project	Researcher	EISG Funding
A Low-NOx Porous Ceramics Burner Performance Study	Florida Institute of Technology	\$75 K
Plastic Solar Cell	Nanosolar	\$75 K
Novel Nanocomposite Carbon Molecular Sieve Membranes	University of Southern California	\$75 K
Build and Test a 3 Kilowatt Prototype of a Co-Axial, Multi-Rotor Wind Turbine	Selsam Innovations	\$75 K
Hydrogen Blower Design for Fuel Cell Recirculation Applications	H ₂ Systems, Inc.	\$75 K
Emission Monitoring of Nitric Oxide With a Mid-Infrared Solid State Laser	The Regents of the University of California, San Diego	\$75 K
Carbon Catalyzed Natural Gas Processing	Sunnyside Technologies, Inc.	\$75 K
Development of Universal Software for Dissolved Oxygen Control in the Activated Sludge Process	Ekster and Associates, Inc.	\$75 K
Radio Frequency Electrostatic System Feasibility Demonstration	EtaTech, Inc.	\$75 K
Self-Optimizing Air Conditioner Controller	Energy Savers International	\$75 K
New Powerline Control Technology for Lighting and Heating, Ventilation and Air Conditioning	Powerline Control Sytems	\$74 K
A Novel Integrated Doubly-Fed Electric Alternator/Active Filter for Wind Power Applications	Texas A&M University	\$75 K
Nanostructured Electrodes for Proton Exchange Membrane Fuel Cells	University of California, Riverside	\$75 K

2.0 2002 Independent Assessment Reports

The Energy Innovations Small Grant (EISG) program awards numerous grants for innovative energy research projects every year. Independent assessment reports (IARs) highlight the project outcomes for each of EISG projects. This section includes the IARs from grant projects that were awarded in 2002 that have yet to be published.

2.1. Sealing and Contacting to Novel Integrated Solid Oxide Fuel Cells

Awardee: Northwestern University
Principal Investigator: Scott Barnett

Introduction

Solid oxide fuel cells (SOFCs) require improved sealing and electrical contacts between cell components if fuel cells are to achieve high efficiency and low cost. Fuel cells are being widely investigated as a more efficient and lower emission generation. SOFCs, in particular, are desirable for grid electrical generation because they can have the highest efficiencies of fuel cell options, and they can work with readily available fuels such as natural gas or with the hydrogen fuel of the future. The SOFC development effort in the United States is primarily focused on the “anode-supported” SOFC design. The U.S. Department of Energy has identified the Integrated Solid Oxide Fuel Cell (ISOFC) as a potentially desirable alternative, and has funded related work on developing this design.

Distributed generation is one of the policy priorities at the California Energy Commission. Advanced fuel cells, including SOFCs, can plan a key role in providing both grid and distributed generation due to the potential for very low emissions and high efficiency. In addition high temperature solid oxide fuel cells can provide significant advantages in combined heat and power applications.

Distributed generation is a particularly advantageous utilization of fuel cell's unique characteristics. The appeal of this approach is not only for improving efficiency, but also the economic advantage of eliminating transmission lines costing up to \$50,000 per mile in remote areas and up to \$1 million per mile in urban areas. The use of fuel cells in distributed generation offers the following potential benefits to California ratepayers: (a) reducing harmful environmental emissions that result from central power plants using combustion technologies, (b) reducing the need for power distribution infrastructure, (c) increasing grid reliability, and (d) increasing grid power quality and eliminating power line losses.

High temperature seals and electrical contacts are a major technical problem for SOFC designs. This project was carried out to develop materials suitable both for sealing and electrically contacting SOFC stack components suitable for use with hydrocarbon fuels.

Objectives

The goal of this project was to determine the feasibility of using silver (Ag) containing braze compositions for sealing zirconia-based SOFC stack components. The principal investigator tested whether these sealing materials could be simultaneously used as electrical contacts in the ISOFC design.

Key project goals were to determine the best braze alloy compositions, and to determine suitable brazing conditions. The investigator achieved these goals by fabricating braze joints and contacts and carrying out a number of different tests. These tests included short term evaluation under realistic SOFC stack operating conditions. One test sequence determined how braze material microstructures changed at elevated temperatures and in the presence of air and fuel gases. Further tests evaluated braze properties including mechanical strength, electrical conductivity, and gas permeability. Finally, the results were combined to achieve a basic understanding of how the braze material responds to these conditions. The specific objectives were:

1. Demonstrate metal braze seals that exhibit high strength and low gas leakage rates.
2. Demonstrate low electrical resistance contacting to the fuel cell stacks using the metal braze materials.
3. Fabricate complete integrated solid oxide fuel cell (ISOFC) stacks using metal brazing for sealing and contacting.
4. Demonstrate good ISOFC stack performance.

Outcomes

1. Six braze compositions were initially evaluated for testing. Four did not adhere to joint materials and were eliminated for further testing. Two metal braze seal compositions provided initial high strength and low leakage rates when joined to joint materials. One is a commercial metal composition, Cusil-ABA and the other was a silver modified form, referred to as Ag-Cusil.

The variability of strength and leakage between multiple samples was an issue for both of these otherwise promising compositions. Most importantly, during elevated temperature testing, both compositions developed microscopic gas bubbles that likely would lead to early strength and leakage failures.

Tensile strength testing was done by simple pull tests. The braze joints showed good tensile strength with values ranging between 12 to 80 megapascals (MPa), but with a lot of variability between samples. However, it was evident that strength degraded over time with exposure to conditions likely to be experienced with ISOFC.

In addition to tensile strength, an important performance characteristic for ISOFC is flexural strength. Flexural strength is an important performance indicator for stack durability, especially in vibratory environments and during transport. Durability of stacks to differential expansion of braze and substrate materials under temperature cycling may also be preliminarily evaluated by flexural strength testing. Flexural strength of the braze joints was not tested.

2. Both braze materials had initial low gas leakage rates. Leakage rate was measured by minimum pressure differential, rather than actual leakage as a percent of fuel/air flow rates. Leakage rates increased significantly after aging in air at elevated temperature. Leakage rates increased by about an order of magnitude. This is an important failure of performance. Once the joints begin to leak (fuel or oxidant), fuel cell performance would dramatically decrease or complete failure would occur.
3. The same two metal braze materials exhibited good electrical conductivity measurements, with one (AgCusil) having higher and more stable conductivity at high temperature (7,000 degrees Celsius.) Both materials demonstrated stable resistivity over the test period of 100 hours. Ag-Cusil had an average conductivity of 4.74×10^5 siemens per centimeter (S/cm); Cusil-ABA had an average of 1.35×10^5 S/cm.
4. The principal investigator successfully fabricated ISOFC using the two metal braze compositions and demonstrated good initial strength, leakage and electrical conductivity. Both sealant/contact materials initially exhibited good performance in a fuel cell configuration as measured by open circuit voltage (OCV). The average OCV for Cusil-ABA was 1.057 volts, while for Ag-Cusil the OCV average was 1.037 volts. Neither actual fuel cell output nor performance with fuel and oxidant was reported. Early in the test, one braze material, Ag-Cusil, failed in mechanical and electrical properties.

Conclusions

Proper composition of metal braze materials may provide good performance in application as ISOFC sealant and contacts. The results of this project did not identify a successful composition and fabrication technique that provides the combination of strength, leakage and electrical resistivity necessary for application in the ISOFC design. Results obtained did indicate that intelligent compositional design may result in braze material with appropriate properties for use in ISOFC designs.

Recommendations

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow on funding within the PIER Program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

The program administrator's recommendation is that additional short term tests, with additional composition and fabrication techniques, be done prior to any long-term test. Given the variability of results and early failures in strength, leakage and gas bubble formation, it is possible that fabrication techniques have been the source of early failure as much as the braze materials' composition. Long-term tests are not justified by the results to date.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is the improved environmental performance of electrical generation in California. If the metal brazing seal material(s) lower the cost and improve the performance of ISOFC, emissions of criteria pollutants and green house gasses from the generation of electricity in California would be dramatically reduced. In addition, expanded fuel cell deployment would facilitate or accelerate the transition to a hydrogen based economy. The program administrator believes it is not practical to quantify potential benefits at this time, but the magnitude of benefits could be quite large.

2.2. Low-Cost, Energy-Saving Motor Controller for Residential and Industrial Buildings

Awardee: The Board of Trustees of the University of Illinois
 Principal Investigator: Patrick Chapman

Introduction

Applications for small, single-phase electric motors are omnipresent among California's residential and small, commercial energy users. Motors of this type routinely power appliances and a wide range of other loads, including fans, heating, ventilation and air-conditioning (HVAC) components, compressors, and pumps. The efficiencies of small, single-phase motors are currently in the range of 78 to 82 percent. They achieve these efficiencies only if they are properly sized to the loads they are driving, and if they are operating at, or near, full design power ratings. Motors frequently drive variable loads such as pumps, hydraulic systems, and fans. In these applications, motor efficiency is often poor (40 to 50 percent) due to operation at low load conditions. In addition, most offer no method of controlling speed in response to changes in the loads they serve.

Variable-speed drives for electric motors to optimize their efficiency have a well-known history. Availability of electronic speed controls has been limited to larger motors because capital-cost premiums and low operational run times allow for reasonable paybacks only in the larger and more continuous operating modes. Commercial and industrial motors routinely utilize variable-frequency drives (VFD) to modulate motor speeds under partial loads in order to reduce excess electrical consumption. VFD technology has not been available for small, single-phase motors, despite the large population of these units.

The commercial and residential sectors in California account for 36.3 percent and 30.3 percent respectively of the total 268,099 gigawatt hours (GWh) of electricity consumed annually in the

state. This consumption produces a coincident peak of 37.7 gigawatts (GW), or 71 percent of the 53.15 GW peak demand for the state. Of this peak, nearly 30 percent is related to weather. Since 2002, when high instantaneous demand created shortages and outages, electric utilities have faced the challenge of supplying and delivering sufficient amounts of electricity during the summer peaks, when customers operate air conditioners and fans. Each of these units contains a small, often single-phase electric motor. Up to 25 percent of the electric load during peak times can be attributed to the use of air conditioners and fans. Any improvement to the efficiency of the electric motors in these devices will reduce peak demand and increase the reliability of the system.

The researchers proposed to increase the efficiency of small motors using a single-phase power source, a three-phase motor, and a variable frequency drive (VFD). Their approach was to modify both the motor and the electronic control to optimize motor efficiency and cost, while using a single-phase power source. Target hardware costs were set at \$40 for a combination of motor, power electronic driver, and controller, which is about \$30 higher than a standard motor alone. The target motor would deliver rated shaft load of 3/4 horsepower (HP) (or 500 watts [W]) at 1,500 revolutions per minute (rpm) with a useful speed-control range of at least 150 rpm to 5,000 rpm, and power efficiency of at least 70 percent for loads ranging from 50 W to 500 W at a specified speed. The researcher chose project objectives that were initially established by the U.S. Department of Energy in its 2003 Future Energy Challenge.

The three-phase motor configuration enables far greater levels of efficiency throughout the motors' operational range, and it extracts superior performance from the materials used in the construction of the requisite rotor and stator components. However, three-phase electrical distribution systems are usually limited to large non-residential facilities. Residential applications would require an alternate method of delivering three-phase power to a small motor.

The proposed systems electric input is 120 volt (V) single-phase. The motor controller consists of a front-end power factor correction (PFC) plus rectifier stage that produces 200 V direct current (DC), while imposing near unity power factor on the input. The PFC leads to an inverter, which delivers variable-frequency, variable-magnitude alternating current (AC) voltage to a three-phase induction motor. A digital signal processor (DSP) board controls the inverter.

Objectives

The goal of the project was to prove the feasibility of an integrated motor-speed controller to achieve reductions in energy losses and costs in residential or commercial applications currently using single-phase motors. The researchers identified three main objectives for this project:

1. Design and construct a 500 watt induction motor and integrated electronic-drive system. The selection of that size reflects the common applications of such a motor. The motor/controller had to operate on standard household single-phase electricity.
2. Perform laboratory tests to demonstrate a minimum operational efficiency of 70 percent across a 10-to-1 speed range for the motor and control system. The integrated drive must

be able to support a full-load output from the motor at speeds ranging from 150 to 1,500 rpm.

3. Design the motor and accompanying control system to meet a manufactured, unit-cost target no greater than \$40.

Outcomes

1. A prototype motor and integrated control system were manufactured and made operational for laboratory tests.
2. The researchers demonstrated improved performance for the motor system, but they did not meet the 70 percent efficiency at any power or speed level over a 10 to 1 power range. The motor itself demonstrated an efficiency of 70 percent or greater over the range of 200 to 500 watts; however, it fell short at low speeds. At the 100 watt level, the motor exhibited an efficiency of 55 percent.
3. The researchers were able to demonstrate compliance with their final market cost objective by obtaining pricing estimates for the manufacture of 10,000 similar units and extrapolating these costs to a production level of 1,000,000 units. Working in association with a major motor manufacturer, the researchers derived a cost estimate for the requisite motor components and developed a unit price of \$37.76 per motor at full production levels.

Conclusions

The researchers did not prove the feasibility of the integrated motor-controller, but they did make significant progress in the development of small electric motors with increased efficiency.

1. The researchers' prototype motor and its performance test results demonstrated that conventional single-phase motors could be replaced with new units capable of operating at higher levels of efficiency with variable speed control that optimize overall system efficiency. The researchers proposed a slotless motor design. They were not able to build this design during the project and, instead, built a standard, slotted induction motor. After this project ended they successfully built and tested a motor based on a slotless design.
2. The prototype motor and drive system met all stated project objectives except at low-load conditions. During the course of the performance tests, the researchers were able to identify the source of that poor performance. Modification of a digital signal processor (DSP) component and its accompanying control algorithm during the project improved low-speed performance. The researchers expressed confidence that, with additional time, a new control algorithm could be written and deployed with the DSP to correct the low-speed performance deficiency. The researchers could have helped the reader understand the progress they made by running a benchmark standard motor under the same conditions and measuring performance. Without this side-by-side comparison it is difficult to assess the potential benefits to California ratepayers.
3. The researchers made a reasonable effort to develop realistic pricing estimates based on the hypothetical production of 1,000,000 examples of the prototype motor. The cost estimate of \$37.76 was extrapolated from component pricing at the 10,000 unit level.

Component suppliers (distributors) were not willing to offer firm quotations at the 1,000,000-unit level for a research project. The methodology of extrapolating the cost from 10,000 units to 1,000,000 units was not well described in the final report. Other factors may be critical at the higher volume level. The entire motor/controller could be redesigned to take advantage of different manufacturing techniques or different components. In addition, at the 1,000,000-unit level a motor-system manufacturer could buy directly from the component manufacturer and avoid the distributor markup. The researchers indicated that aggressive market penetration of the new motor design would require a cost below \$40, perhaps as low as \$20.

4. Although the study proposed applications in the residential and industrial sectors, it appears that efficient small motors are also suited to the commercial sector where three-phase wiring may not exist and loads are active for longer periods of time.

Recommendations

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c), relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow-on funding with the PIER Program.

Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Based on the researchers' statements, the projected efficiency increases may be attainable with additional modification to the motor design. Ultimately, all of the minor design flaws identified by the research team require attention. Additional time allocated to modifying control circuits and their algorithms could yield further improvements to motor performance. This type of development effort can take advantage of opportunities to leverage federal funding, and it can begin to tap the apparent large potential market for this product.

An additional recommendation involves the need to research alternate control inputs for the drive portion of the motor. While the research resulted in a successful internal-control strategy that modulates motor speed in relation to measured decreases in motor loads, the ability to accept external-control inputs should also be included in future work. Larger VFD units operated in non-residential applications are commonly equipped with terminals that allow a variety of external-control inputs to regulate the drive and accompanying motor speed. These external inputs are the basis of load curtailment and demand-response efforts in many facilities where selected motor loads can be modulated during periods of high electrical demand. The research did not indicate if any provision was made in the motor's design to interface with commonly used control systems or communications protocols (0 to 10 volts direct current [DC] or 4 to 20 milliamp signals). While the overall efficiency enhancements of the motor at a static level represent a worthwhile investment, the added ability of these small motors to modulate their speed during constrained peak demand periods represents a substantial value to both end users and regulators in California.

Benefits to California

Public benefits derived from PIER research and developments are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. There is little current data regarding the inventory of small motors and their end-use applications on a statewide basis. Thus, national data compiled by Arthur D. Little was used to approximate the potential benefit of high-efficiency motors in the commercial and residential sectors in California. According to this source, electric motors comprise 4.9×10^{15} British thermal units (Quads), or 26.6 percent, of electric consumption in the residential sector and 3.8 Quads, or 26.3 percent, for the commercial sector. Assuming a similar end-use pattern within California, 94,586 gigawatt-hours are used by electric motors in these two sectors. A significant potential for energy savings exists in these two sectors if motor efficiency can be improved. To evaluate this potential one would have to know the size distribution of the motors, the percentage of those motors with variable loads, and the energy savings potential in each motor class.

Unfortunately the researchers in this project did not provide data for even one direct comparison of motors with and without the integrated controller. Without some direct comparison data, benefit calculations are based on speculation.

2.3. Detecting Optimal Fan Pressure

Awardee: Federspiel Controls
Principal Investigator: Clifford Federspiel

Introduction

Fans for moving air in buildings use a significant amount of energy. Variable-air-volume systems (VAV) reduce the amount of fan energy by reducing the flow when not required. The control systems reduce fan energy in VAV systems by resetting the supply duct static pressure. The standard way to reset duct pressure is by controlling the most-open terminal damper to a nearly open position. However, most systems can't measure terminal damper positions, so pressures are either not reset at all or use ad hoc resetting strategies that are not optimally configured. While many new systems have digital sensors and controls that perform an automatic static pressure reset (SPR), legacy systems are not capable of automated SPR. Many procedures have been implemented to reset that static pressure. Most are manual and require either good engineering judgment, or extensive trial and error.

If an automatic SPR system were in place, electricity could be saved by optimizing the SPR and by locating and eliminating system air leaks. Approximately 29 percent of the commercial air conditioning systems in California are VAV types. The EISG program administrator estimates that, if successful, this project could result in significant energy and cost savings. At the most optimistic end of the estimate, savings could be 510 million kilowatt hours (kWh) per year at 100 percent market penetration using an assumption that 10 percent of the energy could be saved at each location. Under more reasonable assumptions of 5 percent energy savings and a total market penetration of 20 percent, the savings would be 51 million kWh. At an industrial rate of \$0.12 per kWh this translates into a cost saving of \$6.12 million per year. The researcher did not estimate the average savings per installation if his methodology were installed. Any savings estimate is predicated on the commercial availability of an automated SPR system. In addition savings will decline as legacy systems are replaced with modern systems incorporating digital sensors and controls.

This project developed an algorithm that incorporates ad hoc SPR strategies. The goal was to achieve nearly optimal performance using simple sensors. The researcher proposed a new method of determining the critical supply duct pressure for VAV systems. The method relies on a simple functional test and a model of the system behavior. The functional test can be implemented during normal system operation, and can be automated. The system model includes the effect of duct leakage, which offers the potential for dual use as a duct leakage diagnostic. This is important because duct leakage is a significant contributor to inefficiency of air-handling equipment.

Objectives

The goal of this project was to determine the feasibility of using an algorithm to determine the optimal fan pressure to operate VAV air-handling systems under a range of conditions representative of those found in working buildings. The researchers established the following project objectives:

1. Demonstrate 5 percent accuracy in determining critical fan pressures.
2. Demonstrate accuracy in the presence of time-varying controlled flow (closed loop operation).
3. Determine the best flow exponent.
4. Demonstrate insensitivity to pressure sensor location.
5. Demonstrate insensitivity to measurement noise.
6. Quantify the increase in energy efficiency for VAV heating, ventilation, and air-conditioning (HVAC) units.
7. Determine if this algorithm could be used as a leakage diagnostic (added objective).

Outcomes

1. The projected achieved an accuracy of 6.5 percent when the measurement noise was low.
2. The researcher demonstrated the proposed innovation under a range of conditions representative of those found in working buildings. The 6.5 percent level of accuracy

kept the flow within 3 percent of that needed to maintain temperature. Field experiments indicated that moderate errors in measuring critical pressure are not likely to cause discomfort.

3. The researcher determined that the flow exponent that produced the best results was between 0.45 and 0.5. The principal investigator recommended use of 0.5.
4. Accuracy of the critical fan pressure estimates are insensitive to location of the sensor.
5. The researcher found the accuracy of both the critical pressure estimate and the leakage coefficient estimates were inversely proportional to the amount of measurement noise. The researcher developed a relationship between noise and accuracy.
6. The researcher did not address this objective.
7. The researcher's algorithm was used to estimate system leakage in two working VAV air-handling units. Leakage was estimated at 7 percent in one system and 17 percent in the other.

Conclusions

While this project did not meet all of the objectives necessary to prove feasibility, it did demonstrate the possibility that the proposed control algorithm for critical fan pressure may have merit.

1. The project did not achieve its goal of 5 percent accuracy. This may not be critical to the further development of this concept.
2. The methodology met the need of maintaining room air temperature in the comfort zone during period of changing loads.
3. The experimentally determined exponent (0.45 to 0.5) is close to the theoretical value of 0.5.
4. The favorable outcome of this objective allows greater flexibility in performing the needed measurements.
5. Before this sensor/algorithm can be deployed the researcher must establish the acceptable level of sensor noise.
6. The program administrator assumes that the researcher did not address this objective because the project did not meet all of its objectives.
7. Leakage measurement is a valuable ancillary benefit of this control scheme. The researcher should compare this method of leak detection with other available methods.

Recommendations

While the primary objective of achieving 5 percent accuracy was not met, the methodology demonstrated valuable results for commercial buildings with VAV air handling systems. Further work may be justified if the researcher can provide an estimate of potential savings on a large number of buildings. In addition, the researcher must provide a viable development plan to achieve an automated system to reset the static air pressure. Because this innovation is

focused on legacy air handling systems it is imperative to produce a commercial product quickly to capture the greatest energy savings.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow on funding within the PIER Program.

Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. In 1999 commercial buildings in the United States consumed 5.7 Quads (One Quad is equal to 10^{15} British thermal units [Btus]) of energy annually. The program administrator estimates that California commercial buildings used 10 percent or 0.57 Quads of energy in that year. The U.S. Department of Energy further estimates that commercial buildings used 32 percent of the energy for space heating, 3 percent for ventilation, and 7 percent for cooling. While California commercial buildings will have more space cooling and less space heating than the national average, the program administrator assumes that the total of the three space conditioning measures cited above remains at 42 percent. If this percentage is applied to 0.57 Quads of energy, the result is 0.239 Quads used for space conditioning. The program administrator further assumes that only one quarter of this energy is used for air handling. Thus, 0.06 Quads are used for air handling. Using Department of Energy data, the researcher estimated that 29 percent of all commercial floor space is serviced by VAV systems. Therefore VAV systems in California systems consume 0.0174 Quads, or 17.4 trillion Btu. Assuming that the algorithm from this project were applied to 100 percent of the VAV in California and that it resulted in 10 percent savings in the energy consumed by air handling the resulting savings would be 1,740 billion Btu (The researcher did not quantify the potential increase in energy efficiency.). The savings in kWh is 510 million kWh (3,413 Btu/kWh). At \$0.12 per kWh, the savings are worth \$61.2 million per year. The researcher did not provide a commercialization plan or a market penetration plan. Therefore it is not possible to predict the rate of implementation and savings. Additional savings could result from the capability of the algorithm to detect air leakage. No information was provided to quantify the potential energy savings resulting from eliminating the leakage.

While total savings for the state are remarkable, market penetration for the algorithm is likely to be slow since the researcher estimates a savings of \$0.15 per square foot per year (at \$0.15 per kWh). A 10,000-square-foot building would realize savings of at most \$1,500 per year. The researcher did not estimate the cost of implementation of the sensor/algorithm system. Thus, it is not possible to estimate the payback period. Only building managers who are sensitive to energy costs will pursue a change of this nature.

2.4. Fault Location Techniques for Distribution Feeders Containing Distributed Generation

Awardee: Clemson University
Principal Investigator: Adly A. Girgis

Introduction

An electric power distribution system typically has many miles of overhead (OH) conductors and underground (UG) cables. These conductors and cables suffer faults for various reasons. The speed with which these faults can be located, evaluated, and repaired minimizes the customer down time and improves system reliability. The principal investigator indicated that fault-location techniques have been developed that use circuit data measured at the substation to estimate the fault location. These methods have been accurate for radial distribution systems; that model assumes that power flows from only one source, the substation, to the various loads (customers). The fault-current contribution from the substation allows the power company to estimate the location of the fault. The addition of distributed generation (DG) at various customer sites changes the distribution circuit of the power flow. With DG a customer could receive power from various sources. Fault currents would now have components contributed by both the substation and the DG units. These additional fault-current contributions must be taken into account to properly estimate the fault location. The principal investigator identified the need to modify the existing methods to include the contributions of both the fault current and the DG-unit normal current for accurate estimates of fault locations.

The speed with which a cable fault can be located and repaired directly affects the reliability of the distribution grid. In California, the California Public Utilities Commission Decision 96-09-045 imposed electrical-system reliability recording, calculation, and reporting requirements on Pacific Gas and Electric, Southern California Edison, San Diego Gas & Electric, Sierra Pacific Power, and PacifiCorp. There are three indices: System Average Interruption Duration Index (SAIDI) in minutes of sustained outage per customer per year; System Average Interruption Frequency Index (SAIFI), number of sustained outages per customer per year; and Momentary Average Interruption Frequency Index (MAIFI), number of momentary outages per customer per year. SAIDI and SAIFI include sustained outages, which are defined as outages lasting 5 minutes or more. MAIFI comprises momentary outages, which are defined as outages lasting less than 5 minutes. System statistics are computed as follows: (1) including transmission, substation, and distribution outages, and (2) excluding planned outages. Tables 2 and 3 below

show system indices for California. Note that the average distribution customer will experience few outages (less than two) but long ones (over 120 minutes) due to a malfunction in the distribution system.

Table 2. System indices, 1994-2003 (includes transmission, distribution and generation-related outages)

YEAR	Major Events Included			Major Events Excluded		
	SAIDI	SAIFI	MAIFI	SAIDI	SAIFI	MAIFI
1994	160.3	1.721	1.952	155.4	1.540	1.872
1995	600.2	2.616	2.216	170.2	1.537	1.649
1996	347.0	2.462	4.855	178.1	1.709	4.654
1997	171.3	1.700	4.430	161.8	1.639	4.335
1998	317.0	2.130	3.835	180.0	1.659	3.407
1999	157.2	1.481	2.427	156.7	1.477	2.420
2000	168.4	1.413	2.282	167.9	1.410	2.281
2001	249.1	1.560	2.256	211.8	1.439	2.120
2002	381.8	1.672	2.578	139.7	1.114	2.000
2003	198.9	1.328	1.806	193.0	1.308	1.802

Table 3. Distribution system indices, 1994-2003 (excludes outages related to transmission and generation)

YEAR	Major Events Included		Major Events Excluded	
	SAIDI	SAIFI	SAIDI	SAIFI
1994	139.2	1.400	139.2	1.400
1995	536.6	2.393	150.3	1.384
1996	198.4	1.685	167.1	1.632
1997	157.3	1.562	148.4	1.507
1998	245.0	1.812	157.3	1.493
1999	145.1	1.324	144.8	1.321
2000	152.3	1.293	151.8	1.290
2001	228.6	1.430	192.5	1.316
2002	341.2	1.533	129.7	1.030
2003	179.6	1.209	173.8	1.190

Rapid, accurate location of cable faults can reduce the SAIDI index and produce greater grid reliability.

The principal investigator proposed to develop a modified method of fault location for power-distribution lines that include distributed-generation power sources. It would use the recorded substation and DG data before and during the fault and be capable of estimating the fault location within 1 percent error and within 100 milliseconds of a fault occurrence. This would

greatly minimize the time required to locate the exact location of a fault and restore the distribution circuit.

Objectives

The goal of this project was to demonstrate the feasibility of developing a modified method of fault location to account for the presence of distributed generation in a distribution system. The researcher established the following project objectives:

1. Develop a modified method of fault location for power distribution lines incorporating distributed-generation power sources.
2. Demonstrate that the proposed method is capable of locating faults on distribution lines containing distributed generation within 1 percent error.
3. Demonstrate that the proposed method is capable of locating faults on distribution lines containing distributed generation within 100 milliseconds of a fault occurrence.

Outcomes

To establish a baseline for the new method the researcher evaluated the existing “apparent-impedance method” for fault-location estimates on a modeled 10-mile, distributed-generation source. The distribution system was modeled using the Alternate Transients Program. (ATP is a universal program system for digital simulation of transient phenomena of electromagnetic as well as electromechanical nature.) The evaluation results show unacceptable errors in fault location. The error range was from 9 yards to 48 miles.

The researcher also evaluated the existing “three-phase method” for fault-location estimates on a modeled 10-mile, distributed-generation source. The distribution system was modeled with ATP and MATLAB. (MATLAB is a software engineering toolbox for mathematical modeling.) That error range was 60 yards to 63 miles.

1. The researcher demonstrated the developed “modified three-phase method” fault location algorithm on the hypothetical 10-mile distribution system.
2. The researcher simulated single-line-to-ground faults using Power Systems Computer Aided Design/ElectroMagnetic Transients for Direct Current (PSCAD/EMTDC) simulations, and located the faults with an error range of less than 15 yards in 10 miles. This is considerably less than 1 percent.
3. The applicant obtained characteristic data from a “real-world” distribution system with one substation and two distributed generators. Using the same PSCAD/EMTDC software to simulate faults produced the following results: single-line-to-ground faults had an error range of 0 to 195 yards; double-line-to-ground faults had an error range of 1 to 190 yards; line-to-line faults had an error range of 0 to 405 yard; and triple-line faults had an error range of 0 to 360 yards.

Conclusions

The principal investigator in this project developed a modified three-phase method to locate faults in a distribution system that included distributed generation. The data indicate that the developed method is fast and accurate, but it needs more real-world testing and refinement for more complicated configurations.

The principal investigator demonstrated that, based on simulation results, the existing “apparent-impedance method” is not suitable for accurately estimating fault locations on a distribution system with distributed generation.

Similarly, the existing “three-phase method” is not suitable for estimating fault locations on a distribution system with distributed generation.

1. The applicant developed a modified “three-phase method” for estimating fault locations on a distribution system with distributed generation.
2. The modified “three-phase method” was shown to be accurate in predicting fault locations on a simulated distribution system with distributed generation. The error range was 0 to 15 yards.
3. The researcher easily met the objective of locating faults on generation lines within 100 milliseconds.

The researcher indicated that the developed method may need further research for underground cables. It is not clear why the researcher made this statement in the conclusion of the executive summary without additional details in the body of the report.

Recommendations

The modified “three-phase method” for estimating fault locations should be a valued addition to a grid that includes both distributed generation and a high degree of real-time measurement data available for fault analysis. In California, the typical distribution grid does not yet have a high degree of real-time measuring capability. This situation may change as distributed generation becomes more prevalent. The principal investigator indicated that the method should be tested in the real world and in more complex distribution-grid configurations.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow-on funding within the PIER Program.

Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary potential benefit to the ratepayer of this research would be increased reliability of the California electricity system. The higher grid reliability should result in shorter outages, and overall improved customer satisfaction. The developed technique is useful only in areas of the grid where multiple power sources are feeding a circuit and where real-time data is available. In an interview conducted by the program administrator, a Southern California Edison substation engineer commented on the current distribution-system troubleshooting procedures for faulted cables. The basic approach is to allow the existing relays, re-closers, and fuses to lockout the affected section. Alarms are noted at the operational center. After evaluation, a crew is dispatched to investigate and correct the outage. Very few stations are "real-time ready" for telemetry. There are no coordinated means of obtaining real-time data from the qualified generation facilities. In this scenario, the new method of fault isolation may not have much value until more instrumentation and telemetry are installed in California's grid.

Additionally, for any DG site that is capable of exporting power to the grid, the utility requires a fault-current contribution value. This value is then used to update the protection circuitry coordination for that portion of the distribution grid.

A possible application would be to monitor the sub-transmission circuits, or those that link and feed substations. These circuits tend to be monitored in real time, and the necessary data for fault location could be fed into the technique developed by the principal investigator.

2.5. Steady State Security Assessment of Deregulated Power Systems

Awardee: Clemson University
Principal Investigator: Elham B. Makram

Introduction

Today's power systems are highly complex, interconnected networks transferring bulk electric power over wide geographical areas in the western states. The primary aim of any power-system operator is to schedule the available generating sources to match the load demand at the least operating cost. Network disturbances can disrupt this match and cause the network to become unstable, necessitating shutdown. The network operator needs timely knowledge of the onset of instability for a given disturbance on the network. The sooner the operator has this knowledge, the sooner he or she can respond to it. Fast warnings about disturbances can give the operator time to assess a problem and to select the proper response to avoid shutdowns or damage to the network. Network shutdowns have a deleterious effect on California's business climate and directly inconvenience the California electric ratepayer. The research undertaken by this project gives the network operator a computational tool to quickly ascertain the network's stability after a disturbance and allows the operator time to avoid unnecessary blackouts.

A typical disturbance on an electric-power system decouples the load from the transmission system and the generating source for some length of time. This decoupling causes the

transmission-line current to increase, while the transmission-line voltage decreases correspondingly. As the current increases further, a disproportionately sharper drop in voltage is seen. That plunging voltage is the onset of instability. The extent to which the current and voltage vary depends on the type, magnitude, and duration of the disturbance. Mild disturbances, such as corona, will cause current and voltage variations that stay within safe network operating ranges. Lightning strikes or equipment failure can cause voltage and current swings that approach the safe operating limits of the network. The longer these disturbances are present, the more the current and voltage vary from their normal values and lead to instability (voltage drops faster and current rises faster with time). The network operator must start to shut down the network if the voltage and current approach destructive levels. These shutdowns cause blackouts in the regions serviced by the network. A tool allowing the operator to quickly determine the onset of instability after a disturbance would allow the use of methods other than shutdowns to mitigate the effect of the disturbance. The researcher in this project proposed to create and test a computational tool to give the operator quick assessment of the network so many blackouts could be avoided.

Computational tools to assess the status of an electric-power network prior to and after a disturbance have been available to the network operator for some time. Standard Institute of Electrical and Electronics Engineers (IEEE) electric-power-network models have been available to assess the utility of these tools. Computational results using these proven tools and standardized models required expensive equipment. The computations took far too long to be useful to a network operator trying to decide in real time what to do after a network disturbance. The researcher proposed a new computational tool based on an inexpensive personal computer and standard commercial software that uses the network voltage and current to ascertain the stability of the network within a minute.

Objectives

The goal of this project was to determine the feasibility of a computational tool to gauge the likelihood of network instability following a network disturbance. The researchers established the following project objectives:

1. Develop a computational scheme capable of assessing the operating state of a transmission network following simulated power disturbances created on a deregulated network.
2. Demonstrate that the approach developed in this project can provide results in a timely manner with accuracy better than state of the art.

Outcomes

This research produced the following outcomes:

1. The new computational method produced average errors less than 1 percent and maximum errors less than 7 percent in comparison to a traditional load-flow (LF) method that has typical errors of 10 percent when used on several IEEE transmission-line-network test systems. While the new method is accurate, it is not significantly more accurate than the load-flow method.

2. The new method is faster in some cases by a factor of 10. Computation time was less than the traditional load-flow method in all cases.

Conclusions

This research has created a computational tool that uses a personal computer loaded with a readily available software package to calculate how close the network is to instability.

Instabilities quickly lead to network destruction, so shutdown must be initiated before they start. This new tool calculated network proximities to instability faster and within 7 percent maximum errors when compared to standard load-flow methods run on standard IEEE network test systems.

This research produced the following conclusions:

1. The computational tool produced fewer than 7 percent errors maximum when evaluated on several IEEE standard network test schemes. This is as good, or better in some cases, than the current load-flow method.
2. The computational tool is significantly faster than the current load-flow method when evaluated on several IEEE standard network test schemes.

Recommendations

Further research should use actual network data instead of the standard network test schemes to evaluate the new tool. The new tool should also address transient disturbances.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow-on funding within the PIER Program.

Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is increased reliability of the California electricity system. The California electricity system is controlled by a network operator responsible for providing sufficient generating power sources over a vast electrical transmission-line network for a fluctuating electrical load. The generating power sources are electrical utilities located in California or power purchased out of California and transmitted into California over interstate transmission lines. The electrical load arises primarily from the

demands California ratepayers place on the system, and it varies as electricity consumption changes throughout the day. It is the network operator's job to provide the ratepayer with the electricity needed on a 24/7 basis. Any disturbance in this source/transmission-line/load scheme can create significant financial penalties for the electrical generators, the network operator, and the California ratepayer.

Network operators have computational tools to establish the voltage and current values on a network transmission line. These tools were created using standard IEEE test systems that simulate disturbances on a number of transmission lines connected together. Computation times are long compared to the time for disturbances to reach destructive levels, and the equipment needed is complex and expensive. If the software tool developed in this project were to become a supported and accepted methodology, it would give the system operator quicker answers to the question of potential instability.

The computational tool created by this research would enable the California network operator to quickly assess the stability of a transmission network after a disturbance has occurred on it. This assessment will enable the network operator to take corrective/ preventive action to ensure network reliability and reduce the possibility of power blackouts. The reduction of power blackouts will benefit California ratepayers.

2.6. High Efficiency Organic Thin Film Solar Cell

Awardee: Interphases Research
Principal Investigator: Shalini Menezes

Introduction

Distributed generating systems powered by renewable forms of energy would reduce the consumption of carbon-based fuels by utilities and, importantly, slow the need for new, large-scale generating plants and transmission lines. A photovoltaic (PV) system integrated into building rooftops to capture solar energy could provide maximum power in the afternoons, when peak insolation nearly coincides with peak commercial electricity demand. (Insolation is a measure of solar radiation energy received on a given surface area in a given time.) Energy generated in excess of need could be exported to the grid to reduce the existing imbalance between peak electric demand and supply in the state. The barrier to wider use of PV generation of power has been the high initial cost of the predominant, crystalline-silicon solar modules. These modules account for 93 percent of the PV market. A flexible, organic-film-based PV made by roll-to-roll processing would offer many advantages, including lower material cost, lower manufacturing cost, and greater ease of rooftop deployment, thanks to its flexible nature. Efforts to construct inexpensive organic photovoltaic (OPV) cells have been frustrated by their short diffusion lengths of excited electrical carriers and their low conversion efficiency of 1 to 2 percent. An efficiency of at least 5 percent is desirable to lower their capacity cost and to reduce the area needed for power generation.

Crystalline-silicon PV modules have a capacity cost of \$3.74 per watt (W). The photovoltaic industry has established a cost goal by the year 2010 of \$1.50 per watt-peak (W_p) for PV modules. That would make PV broadly competitive in the residential market without subsidies. The researcher in this project predicted a capacity cost of \$0.46 per W for an organic photovoltaic (OPV). If achieved, this would establish the OPV as more competitive in the longer term and of greater benefit to the ratepayer. The project based the estimated operating cost of the organic solar-cell system on a projected OPV device of 5 percent efficiency. Assuming a module selling price of \$0.60 per watt-peak (W_p) and other installed balance-of-system cost at \$0.90 per W_p, the overall cost for solar-generated electricity would come to \$0.05 per kilowatt hour (kWh). This compares favorably with natural-gas-fired, combined-cycle generating plants that produce electricity at \$0.052 per kWh, with installed capacity cost of about \$1 per W.

The proposed OPV device is based on a molecular bulk hetero-junction. The scientific advance proposed to overcome the short diffusion lengths of excited electron and hole carriers, and the concomitant low-power efficiencies, is a novel bulk or blend hetero structure. It uses small-molecule, semiconducting, organic compounds that are phase separated as donor and acceptor. Together, they have a relatively good match to the solar spectrum and cover a range from 400 nanometers (nm) to 900 to 1,000 nm. They are further blended with a high-mobility conducting polymer material. A semiconducting hole-transporting layer (HTL) facilitates the transport of holes to the electrode, and an optional electron-transfer layer facilitates electron transport. The researcher proposed that charge separation be achieved by “molecular bulk hetero-junction” in the blend layer at the molecular level, as opposed to planar hetero-junctions at a bi-layer interface. The goal was to find working materials, fabricate a solar cell, and achieve an open-circuit voltage and necessary power efficiency.

Objectives

The goal of this project was to determine the feasibility of developing a low cost solar energy conversion device based on the concept of molecular bulk hetero-junction charge separation with an organic blend absorber thin layer. The researchers established the following project objectives:

1. Develop a simple, low-cost methodology for fabricating the proposed, flexible, organic solar cell.
2. Fabricate molecular bulk hetero-junction solar-cell devices for testing.
3. Demonstrate organic photovoltaic device potential for conversion of solar energy.
4. Demonstrate a cell efficiency of greater than 5 percent.
5. Show from the project data that the projected module manufacturing cost of \$0.46 per watt for the new solar cell is valid. This represents a cost reduction of 85 percent over current, state-of-the-art, crystalline-silicon, solar cells, or \$3 per watt(W).

Outcomes

1. The researchers made a general case that the materials and the projected flexible device would be adaptable to roll-to-roll, solution-coating techniques. However, the experimental work did not proceed far enough to actually demonstrate roll-to-roll fabrication.

2. Fabrication of actual solar cells was not demonstrated.
3. Deposited films of different organic materials were subjected to voltage and current measurements under photo-illumination and to chemical tests. Some qualitative photo-activity was observed, but the electrical measurements were not quantitative.
4. No efficiency measurements were made because a working solar cell was not fabricated.
5. Cost estimates projected that if the solar-cell efficiency of 5 percent could be achieved, then modules could be manufactured for \$0.36/W (an improvement over the goal of \$0.46/W) and electricity produced at \$0.05/kWh. The materials were not specified.
6. A spin-off outcome came from qualitative measurements on a hybrid organic/inorganic (copper indium selenide) hetero-junction that showed some photo-current under illumination. However, the lack of quantitative measurements allows no assessment of this result.

Conclusions

1. Although the experimental work did not proceed far enough to actually demonstrate roll-to-roll fabrication, it seems reasonable that such an approach is worth investigating and could produce a successful outcome.
2. Since no working organic solar cells were fabricated, it is not yet possible to draw firm conclusions about their technical feasibility or potential.
3. While deposited films of different organic materials were subjected to voltage and current measurements under photo-excitation, the lack of quantitative measurements makes it impossible to assess the significance of the results for solar-cell fabrication.
4. This important objective of demonstrating a solar-cell efficiency of greater than 5 percent was not met. The lack of a working solar cell precluded measurements of efficiency.
5. Without the prescribed data it is not possible to determine the cost of electricity generated by solar cells incorporating this design.
6. The lack of quantitative measurement makes it difficult to assess the significance of the spin-off, hybrid, organic/inorganic hetero-junction results.

The proposed goal of this project was to verify the feasibility of the concept of molecular bulk hetero-junction charge separation with an organic-blend-absorber thin layer for a high-efficiency, organic, thin-film solar cell. Successful fabrication of a working solar cell would have verified the feasibility of the concept, and demonstrating a power efficiency of 5 percent would have been persuasive. A qualitative change in photocurrent of an unknown magnitude is not persuasive. It is common to see some change in the electrical properties of non-conducting materials under illumination due to carriers excited across gaps and photo-excited surface states, but that alone does not prove the feasibility of a molecular bulk hetero-junction cell.

Recommendations

The program administrator recommends that the researcher fabricate a working organic-blend-absorber cell. Quantitative measurements of its properties would allow the status of the concept to be assessed and serve as a benchmark for further improvements in cell materials and design.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research, if the goals were met, would be increased affordability of electricity in California. A flexible, organic photovoltaic cell produced by roll-to-roll processing has low-cost potential. Data reported in this project is insufficient to permit estimates of the cost of a real product.

2.7. Unified Power Quality Conditioner Using One-Cycle Control

Awardee: University of California - Irvine

Principal Investigator: Dr. Keyue Smedley

Introduction

Quality problems in the generation of electricity, such as variations in voltage, prevent the use of 10 to 20 percent of the total rating of every electrical substation. Further, the intermittent production of many renewable energy sources limits their ability to contribute to the power supply. For example, only about 30 percent of wind-power generation stations are on the grid at a given time because a higher percentage could cause the power-quality profile to fall below utility specifications.

Assuming that 10 percent of this poor-quality, non-renewable energy could be made usable at 50 percent of all substations, California could realize a \$1.3 billion per year savings. An increase in the quality of wind power that allowed an additional 10 percent of existing wind-power stations to operate on the grid at a given time could yield an additional \$180 million per year savings. Better power quality would produce indirect savings by reducing the number of incidents in which utilities incur fines for failing to provide power within defined quality specifications. Finally, by utilizing a higher percentage of the power generated, California would benefit from lower emissions resulting from reduced production for a given demand.

The researcher proposed a Unified Power Quality Conditioner (UPQC) using One-Cycle Control (OCC). This device would be connected on the utility side of the substation to control power flow, regulate the voltage against sag/swell, and eliminate harmonic and reactive current. The researcher proposed integration of an OCC and indicated that integration was the key to the device's simplicity, reliability, and cost-effectiveness.

Objectives

The goal of this project was to determine the feasibility of using the OCC as part of a Unified Power Quality Conditioner (UPQC) in order to correct reactive power flow, suppress harmonic distortion, and regulate voltage variation/sag. The researcher established the following project objectives:

1. Build a 5 kilowatt (kW), three-phase, bench-scale prototype of an OCC-UPQC.
2. Demonstrate that the OCC-UPQC has the following capabilities:
 - a) Energy efficiency over 93 percent.
 - b) Power factor over 98 percent.
 - c) Residual total harmonic distortion (THD) less than 5 percent.
 - d) Maintain load-side voltage within plus/minus 10 percent, with source voltage variation up to 50 percent (within specified constraints).
3. Show that the project results support the projected device cost of \$100 per kW.

Outcomes

1. The researcher successfully constructed a 5 kW OCC-UPQC as proposed.
2. The OCC-UPQC was tested with loads varying from 2.8 kW to 4.1 kW, introducing steady state and transient voltage disruptions.
 - a) Energy efficiency of the OCC-UPQC was not demonstrated through testing.
 - b) Power factor of the OCC-UPQC was not demonstrated through testing.
 - c) Residual THD ranged from 3.9 percent to 6.9 percent. Results are summarized in Table 4.

Table 4. Total Harmonic distortion suppression

Case	Description	Initial THD	Final THD1
1	33% single-phase sag and harmonics	16.5%	3.9%
2a	20% two-phase sag and harmonics	13.8%	<5%
2b	33% two-phase sag and harmonics	16.5%	<5%
3a	12% three-phase sag and harmonics	14%	<5%
3b	18% three-phase sag and harmonics	14%	<5%
3c	33% three-phase sag and harmonics	16%	<5%
4	Harmonic current compensation – 2.8 kW load	30%	5.3%
5	Harmonic current compensation – 4.1 kW load	25%	5.3%
6	Reactive power compensation – 0.9 kW load	24%	6.9%

1. Actual data values <5% were not presented.

- d) Voltage variations were maintained within plus/minus 10 percent, with voltage variations up to 33 percent, and a voltage spike of 47 percent. The majority of the variations used fell short of supporting the original objective, with voltage variations up to 50 percent. Results are summarized in Table 4. Current regulation results are presented in Table 5.

Table 5. Voltage compensation (tolerance from ideal voltage)

Case	Description	Initial V Variation	Final V Variation
1	33% single-phase sag and harmonics	33%	<5%
2a	20% two-phase sag and harmonics	20%	<5%
2b	33% two-phase sag and harmonics	33%	<5%
3a	12% three-phase sag and harmonics	12%	<5%
3b	18% three-phase sag and harmonics	18%	<5%
3c	33% three-phase sag and harmonics	33%	<5%
7	Momentary voltage sag	33%	<5%
8	Voltage spike	47%	<5%

Table 6. Current compensation (unbalance ratio)

Case	Description	Initial I Variation	Final I Variation
9	Unbalanced current regulation	42%	7.7%
10	Neutral current limitation	46%	7.7%

3. This objective was not met. The researcher did not prepare a cost analysis to support the device cost goal of \$100 per kW.

Conclusions

Project feasibility was not met.

1. The objective of constructing a bench-scale 5 kW OCC-UPQC was met. This prototype was used in testing voltage and current disruptions under loading up to 4.1 kW.
2. Testing of the prototype was not sufficient to fully meet this objective.
 - a) The objective to demonstrate energy efficiency over 93 percent was not met. No data were presented related to the energy efficiency of the OCC-UPQC.
 - b) The objective to demonstrate power factor over 98 percent was not met. No data were presented related to the power factor of the OCC-UPQC.
 - c) The objective to demonstrate a residual THD of less than 5 percent was nearly met. Various cases tested resulted in a residual THD ranging from 3.9 to 6.9 percent. Actual data were not presented for most cases; rather, they were stated as less than 5 percent THD.

- d) The objective to maintain load-side voltage within plus/minus 10 percent, with source voltage variation up to approximately 50 percent, was met, although only a single variation pattern at the upper end of this range was tested. Actual data were not presented for voltage variation cases; rather, they are stated as within 5 percent amplitude of the ideal voltage. The researcher further demonstrated that the unbalance ratio on current could be reduced to within plus/minus 10 percent, with current variation up to approximately 50 percent.
3. The objective to show from the project results that the projected device cost of \$100 per kW capacity was not met. No cost analysis or data were presented.

The original goal of the project was to determine the feasibility of using the OCC-UPQC system to correct reactive power flow, suppress harmonic distortion, and regulate voltage variation/sag within the proposed tolerance. Laboratory data presented suggest that the OCC-UPQC can effectively regulate such variations; however, testing was incomplete and did not address all of the originally stated objectives. The researcher proposed a device cost of \$100 per kW, but no data or analyses were provided to support this cost.

Recommendations

The researcher should consider the following recommendations upon commencement of additional work in this area:

1. Conduct testing to validate the objective of 93 percent energy efficiency.
2. Conduct testing to validate the objective of a power factor over 98 percent.
3. Present a cost analysis for component construction at various scales (75 kilovolt amps [kVA], 250 kVA, 1,000 kVA).
4. Present support for assumptions in calculation of cost benefit to California. For example, show quantitatively that the OCC-UPQC would make usable 10 percent of otherwise poor-quality, non-renewable power. Other assumptions are listed in the Introduction of this section.

While the OCC-UPQC technology appears promising, the researcher should develop additional data and supporting cost estimates prior to requesting additional funding.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is an improvement in the reliability and quality of both renewable and non-renewable energy generation. California's yearly energy consumption is presently approximately 2.65×10^{11} kWh. Approximately 10 to 20 percent of the

total power produced cannot be used due to reactive and harmonic current flow. Similar restrictions hinder renewable energy sources. Only about 30 percent of existing wind-power stations operate on the grid at a given time, as an increase in this percentage may cause power quality to fall below specifications.

Incorporation of the OCC-UPQC could allow better utilization of existing, non-renewable power sources and provide more capacity for renewable ones. Assuming that 10 percent of the poor-quality, non-renewable energy could be made usable at 50 percent of all substations, California could realize a \$1.3 billion per year savings. This calculation is based on California's average annual consumption using a rate of \$0.1 per kWh. Improvement of wind-power quality sufficient to allow an additional 10 percent of existing wind-power stations to operate on the grid at a given time could produce another \$180 million per year savings.

Additional environmental benefits could accrue from a more efficient electric supply system. Assuming the same demand level with increased efficiencies, airborne emissions from non-renewable sources may decrease annually by:

Sulfur dioxide (SO ₂):	22,000 tons
Nitrogen oxides (NOx):	14,000 tons
Carbon dioxide (CO ₂):	4,300,000 tons

2.8. Methane Sensor for Control and Automation

Awardee: Carthago International Solutions, Inc.
Principal Investigator: Dr. Mourad Baraket

Introduction

There is increasing pressure to deploy facilities powered by renewable energy to add generating capacity, improve system reliability, and help stabilize California's electricity prices. Major renewable energy sources currently under research and development in the United States include solar, wind, geothermal, hydrogen, and biomass. Biomass-derived energy includes the combustion of renewable sources such as wood waste, and the combustion of the biogas derived from anaerobic decomposition of organic materials in landfills; other sources of anaerobic decomposition derived biogas include municipal sewage-treatment facilities and the decomposition of manure from animal feed lots and dairies. Biogas derived from anaerobic decomposition contains methane, carbon dioxide and small amounts of other gases such as nitrogen, oxygen, water vapor and hydrogen sulfide, with methane being the component of interest for energy production. The composition of landfill biogas varies with the characteristics of the waste, age of the landfill, weather conditions, and others factors. While there has been some success in turning biogas into electricity, it is frequently just flared off due to difficulties in its proper control. It is significant that the amount of methane in biogas varies widely from 35 to 60 percent. To control the process conditions, and to insure that dangerous amounts of oxygen from infiltrating air are not contaminating the product during the extraction process, it is desirable to measure the content of methane present. Measurement of the actual concentration of methane in the extracted gas stream will also lead to better control over stoichiometry and thus increased efficiency during its combustion to drive electrical generation; it is estimated that an increase in conversion efficiency in power generation of 10 to 15 percent can be achieved. This project is for the development of a quantitative methane sensor to monitor the biogas composition in real time during extraction from decomposing organic waste in landfills.

California leads the nation in solid waste generation with an estimated 76 million tons of waste produced each year. Of this waste, over 20 million tons are energetically valuable organic materials, of which almost 15 million tons are put in landfills each year. California also leads the nation in number and size of landfill gas to electricity (LFGTE) facilities. The Puente Hills landfill, operated by the Los Angeles County Sanitation District, produces approximately 46.5 megawatts (MW) of power and is the largest LFGTE facility in the United States. There are 311 active landfills in California with 42 producing biogas to generate 211 MW of electricity, seven others produce heat, and two other landfills inject natural gas into existing pipelines. Biogas is being produced at 70 other landfills but is simply being flared; the biogas they produce has a potential for 66 MW. There are 164 landfills that either do not have biogas control systems or are venting the biogas; these 164 landfills have the potential for producing approximately 31 MW of electricity. Although it has been concluded that most of the opportunities for "big" systems are gone, an increase in conversion efficiency of 10 to 15 percent could produce substantial savings. In this regard, it would appear that California landfills have the potential for about 300 MW of electricity generation capacity overall. This capacity corresponds to a

potential electricity market of 2.6×10^9 kilowatt hours (kWh) per year. Assuming the cost of electricity as that of from natural gas fired combined cycle generating plants of about \$0.052 per kWh, the total market size for landfill gas to electricity would be $\$1.4 \times 10^8$ per year. An increase in conversion efficiency of 10 percent would therefore have a market value of $\$1.4 \times 10^7$ per year.

The chief scientific goal of this project is the development of a sensor system to measure methane (CH_4) concentration in a biogas mixture. The sensor must be accurate and with fast-response to monitor methane concentration in real time during extraction. The device proposed, a photoacoustic sensor (PAS), is based on a measurement cell covered by a special gas permeable membrane. A lamp emits filtered light of wavelength tuned to an absorption band of methane. The light intensity is periodically modulated at a frequency in the low audio range. Absorbed light in the cell then periodically modulates the temperature of the gas. Since the membrane is designed to allow gas to permeate through it only for times long compared to the millisecond modulation period, the temperature pulses result in pressure pulses in the cell. The microphone transducer converts the varying pressure pulses to a time varying electrical output that can be monitored. The membrane, however, allows gas to permeate over times that are long with respect to a modulation period so that the gas in the cell remains in equilibrium with its surroundings. The degree of light absorption is proportional to the concentration of methane in the cell, and thus the magnitude of the pressure pulses can be calibrated against methane concentration.

Objectives:

The goal of this project was to determine the feasibility of a new gas sensor to control and automate the collection of biogas and the operation of distributed power generators (e.g. microturbines and fuel cells). The sensor will contribute in achieving the competitiveness of biogas-to-electricity systems. The researchers established the following project objectives:

1. Design/build a bench-scale prototype for extensive tests to determine the sensor performance
2. Confirm from data generated that projected sensor lifetime of 10 years continues to be supported
3. Confirm from data generated that projected unit cost of \$2,500 continues to be supported
4. Demonstrate the following operating parameters:
 - a) Measurement range: 10 to 80 volume-percent of CH_4 in air
 - b) Lowest detection: 5 percent volume-percent of CH_4 in air
 - c) Measurement Accuracy: 2 percent full scale
 - d) Response time T90 percent: 60 seconds
 - e) Recovery time T100-10 percent: 60 seconds
 - f) Warm up time: 30 seconds
 - g) Operation temperature: -20 degrees to 50 degrees Celsius

- h) Operation humidity: 5 to 95 percent relative humidity

Outcomes

The researchers' discussion of the approach and outcomes of the research could have been impeded because of the fact that the report declares that all results of the research are "confidential." This would appear to be an overapplication of the term "confidential" since it uses an established technique (photoacoustic sensor) and it would limit our ability to present a report of an independent assessment of the research. Here the authors present a review of the research results leaving out a few technical details that are not needed to assess the results, and request that this report be given to the principal investigator for comments before it is released.

1. Objective 1 to "Design/build a bench-scale prototype for extensive tests to determine the sensor performance" was successfully accomplished. The prototype methane measurement system consisted of a sensor subsystem containing the active gas measurement volume, light source, microphones, reference gas volume chamber, two circuit boards, for microprocessor control voltage measurement. A separate control box supplied power and a data link to the sensor. These subsystems were successfully fabricated and assembled. Operating software was written and operation of the system was demonstrated.
2. Objective 2 was to "Confirm from data generated that projected sensor lifetime of 10 years continues to be supported." It is stated in the Executive Summary that this objective continues to be supported. However, no specific results were cited in the report.
3. Objective 3 was to "Confirm from data generated that projected unit cost of \$2,500 continues to be supported." It is stated in the Executive Summary that this objective continues to be supported. However no specific results were cited.
4. Objective 4 was to demonstrate the following operating performance parameters:
 - a) Measurement range: 10 to 80 percent volume-percent of CH₄ in air
Testing in "synthetic" air demonstrated detectivity to methane from 1 to 100 percent. Measurement resolution was satisfactory up to 60 percent. Above 60 percent, particularly above 70 percent, resolution is less than adequate. It is noted that methane concentrations above 70 percent are not expected in the target application.
 - b) Lowest detection: 5 percent volume-percent of CH₄ in air
This objective was surpassed by a substantial margin with sensitivity down to 1 percent methane in "synthetic" air.
 - c) Measurement Accuracy: 2 percent full scale
Actual accuracy testing was not reported. However tests for measurement repeatability at 40 percent methane in air showed a standard deviation of measurement of about 0.6 percent methane. Good repeatability is necessary (but not sufficient) for good accuracy.
 - d) Response time T90 percent: 60 seconds
Response time measurements were not reported.

- e) Recovery time T100-10 percent: 60 seconds
Recovery time measurements were also not reported.
- f) Warm up time: 30 seconds
Warm up time measurements were also not reported.
- g) Operation temperature: -20 degrees to 50 degrees Celsius
Test data are reported for four ambient temperatures from -20 degrees to 50 degrees Celsius. A strong (and complicating) monotonic variation in sensor output with temperature was observed.
- h) Operation humidity: 5 to 95 percent relative humidity (RH)
This sub-objective was partially met. Test data are presented for relative humidity values of 0, 32, and 68 percent, and methane concentrations of 0, 11.08, and 28.75 percent. Over these limited ranges the data show little dependence on relative humidity, a desirable outcome.

Conclusions

1. Objective 1 to “Design/build a bench-scale prototype for extensive tests to determine the sensor performance” was successfully accomplished. Pictures of the prototype in the report show a professional degree of fabrication skill and are as would be expected for a prototype that could make a successful transition to a marketable instrument.
2. Objective 2 was to “Confirm from data generated that projected sensor lifetime of 10 years continues to be supported. This objective was not met. In this regard it is significant that the sensor employs pulsed electrically heated filaments emitting infrared radiation. Everyday experience with the lifetime of incandescent light bulbs suggests that these filaments could be a weak link in the lifetime of the system. Another potential weak link could be fouling of the gas permeable membrane by gas-born particulates. Proper gas filtering in front of the sensor will be necessary.
3. Objective 3 was to “Confirm from data generated that projected unit cost of \$2,500 continues to be supported.” Since no data or discussion in support of this objective are in the report, it would appear that this objective still has to be demonstrated. One would like to at least see some data on the cost of some of the more costly components in the sensor such infrared filter, microphone, light source.
4. Objective 4 was to demonstrate the following operating performance parameters:
 - a) Measurement range: 10 to 80 percent volume-percent of CH₄ in air
Although this sub-objective was not completely met it appears that very good progress was made. The shortfall was in the high end of the composition range, outside of what is expected in the field for the target application. Accordingly this shortfall does not appear to be too serious.
 - b) Lowest detection: 5 percent volume-percent of CH₄ in air

This sub-objective was exceeded to a substantial degree. In fact the greater level of detectivity achieved may open up new applications for the instrument.

- c) Measurement Accuracy: 2 percent full scale

Although actual accuracy testing was not reported, some measurement repeatability tests display good repeatability. Good repeatability is a necessary condition for high accuracy.

- d) Response time T90 percent: 60 seconds

This sub-objective does not appear to have been demonstrated since no data are given.

- e) Recovery time T100-10 percent: 60 seconds

This sub-objective does not appear to have been demonstrated since no data are given.

- f) Warm up time: 30 seconds

This sub-objective does not appear to have been demonstrated since no data are given.

- g) Operation temperature: -20 to 50 degrees Celsius

Test data indicate that this objective was partially met. It is likely that the variation of sensor output with temperature could be taken into account through ambient temperature measurement and a microprocessor-based calibration curve. However no such approach was reported.

- h) Operation humidity: 5 to 95 percent relative humidity

This sub-objective was partially achieved. Test data over a partial range from 0 to 68 percent relative humidity are encouraging and indicate that relative humidity variation will not be a problem.

Overall the project objectives were only partially achieved. The objectives not achieved, however, were not achieved because of a lack of data rather than counter indicative data. No "show stoppers" were reported. Importantly, the researchers did succeed in building a working prototype instrument (Objective 1) and testing some (but not all) of the more important performance parameters (Objective 4). The program administrator had a question regarding the justification for the use of the methane sensor in biogas extraction, namely to monitor for explosive air infiltration into the biogas stream, and why an operator would not prefer an actual oxygen sensor for monitoring air infiltration.

Recommendations

Some good progress was made; however the program administrator has a couple of concerns. One concern is the misapplication of the category of "confidential" to the entire project approach and outcomes. This approach is well known to segments of the technical community, going by the name of "photoacoustic spectroscopy" (PAS) or alternatively "optoacoustic gas sensing. The technique goes back as far as 1880 in the work of A.G. Bell, and there are a number of entire monographs devoted to it. There is a journal literature on PAS development. There are

commercial instruments on the market that use PAS for methane detection. Some of these facts were acknowledged by the principal investigator in the proposal but are not mentioned in the final report. Also a 1999 U.S. patent “Optoacoustic gas sensor” appears to have considerable overlap with the present project. The program administrator recommends that this earlier work just mentioned be reviewed for potential relevance and the review would have the beneficial effect of illuminating what is most unique here. The program administrator also recommends that the researchers look into application of the methane sensor to mine safety. The accumulation of methane in coalmines can be a serious safety problem.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research would be “reduced environmental impacts of the California electricity supply or transmission or distribution system” since it is a substitute for fossil fuel. The development of an accurate fast-response methane sensor would increase the attractiveness and efficiency of biogas production and its use in electricity generation. The addition of grid-connected biogas-derived electrical capacity would incrementally reduce the need for new fossil fuel-generating plants. In addition there is the attractive possibility to capture environmental benefits such as reductions in odor, air, and groundwater pollutants associated with processing livestock manure, food processing, wastewater and landfill wastes.

2.9. Instant Snap-In Load Shed Device for Incandescent Lighting

Awardee: Rensselaer Polytechnic Institute
Principal Investigator: Richard M. Pysar

Introduction

This project evaluated techniques for controlling incandescent lighting power consumption as part of load shedding schemes to reduce peak loading on the electrical grid by remote signaling. If such a load shedding activity were widespread, the peak power load on the electrical grid could be reduced during critical times of high power demand. Many people do not notice lighting level reductions of up to 50 percent, at least for short periods of time. In order to make a low-cost and easily installed solution to this problem, a screw-in device for Edison socket bulbs was the focus of the project.

Peak power needs in California could be reduced by up to 50 megawatts (MW) if a few percent of incandescent light bulbs receive less power following a remote command. At critical times, such as rolling blackouts, the possibility of the reduction of power use is equivalent to having additional generating capacity, and the 50 MW figure could represent a gas turbine generator that costs tens of millions of dollars to build and have available for use during peak power events.

Incremental peak power in California is expensive; a kilowatt-hour of reduced energy demand at critical times could be worth ten times the base rate. The value of 50 MW of reduced demand could be worth \$50,000 dollars an hour, or \$5 million a year for 100 hours of critical load reduction. This level of load reduction would result from 1 million light bulbs having their power consumption each decreased by 50 watts.

The proposed solution to this problem is the use of power lines for signaling in conjunction with the development of reliable communication and control units for each light bulb. Several approaches to power line signaling were under investigation, and the research undertaken in this project concentrated on evaluating several of those efforts. In order for customers to pay for installing the load-shedding feature on their bulbs, the price per bulb must be low. One of the goals of this project was to investigate techniques for lowering the cost of such controls.

A related scheme was also being evaluated by the Lighting Research Center, *Energy Efficient Load Shedding*, for controlling fluorescent lighting. Some of the focus on how to use remote signaling for control is related to this parallel effort.

Objectives

The goal of this project was to determine the feasibility of developing incandescent lighting equipment that can shed electric load on demand. The researchers established the following project objectives:

1. Fabricate a prototype load shed device for incandescent lighting in the range of 25 to 150 watts.
2. Demonstrate that the device is capable of receiving the same power-line signal used in load shedding ballasts for fluorescent lighting.
3. Demonstrate that the power-line signal is capable of both activating and deactivating a specific level of dimming in an incandescent lamp.
4. Demonstrate that the load shed device can operate safely and reliably under the electrical and thermal conditions found in typical incandescent lamp sockets.
5. Demonstrate that the load shed device can be miniaturized to a size that does not adversely affect the position or safe operation of the lamp.
6. Demonstrate that the prototype load shed device can reduce power consumption of incandescent lamps by 30 to 50 percent on demand.

Outcomes

1. Early in the project the researcher determined that it was not possible to develop a snap-in adaptor. The researcher developed a screw-in adaptor that operated in the range of 25 to 150 watts over most conditions. Due to high temperatures, the screw-in device could

2. The researcher could modify the incandescent adaptor, developed in this project to work with any of the power line communication systems tested.
3. There is no test data in the final report to indicate that the researcher investigated the capability of activating and deactivating to a specific level of dimming.
4. The thermal operating parameters of a typical incandescent lamp socket and fixture were determined: The worst-case internal environment is near 120 degrees Celsius. For the base-down condition, the internal temperature is less than 85 degrees Celsius for all four tested conditions, including the worst-case condition of a 150 watt lamp in a fixture that is enclosed on the sides. For the base-up condition, the internal temperature is nearly 85 degrees Celsius with a 100 watt lamp, and approximately 90 degrees Celsius with a 150 watt lamp, in a fixture that is not enclosed on the sides. When the fixture is enclosed on the sides, the internal temperature with a 100 watt and 150 watt lamp increases to about 100 degrees Celsius and 120 degrees Celsius, respectively. Thus, the temperature specification goal became 125 degrees Celsius. Therefore, 85 degrees Celsius industrial-grade components would be marginally adequate for base-down applications, and 125 degrees Celsius military-grade components would be required for base-up applications.
5. Since the researcher used commercially available subsystems, he was constrained by the size of those units. The only constraint on safe operation was the temperature of system components when used with high-wattage light bulbs in base-up operation.
6. Three locations near Troy, New York, were used for testing. The Lighting Research Center, the Greene Building on the Rensselaer campus and the Curtis Lumber store in Ballston Spa, NY were the test sites selected. Testing focused on behavior of the power line communications (PLC) aspect of the five combinations that were included in the final evaluation. Only the Ariane Controls combination actually turned down the light bulb intensity; the other four combinations turned on led indicators to show that they had received the load-shed command. Tests were set up with a transmitter connected to the power lines in the building, and the load-shed devices were then plugged into outlets around the building. A variety of devices were in use in the building and represented typical power line loading that can lead to failures in the power line communication tests. No tests were reported to show that the power level was reduced by 30 to 50 percent on demand.

Conclusions

1. The researcher did not prove feasibility of a snap-in device.
2. This objective was met.
3. This objective was not met.
4. With the exception of high wattage base-up bulbs, this objective was met. The high wattage bulbs require the use of electronic devices meeting the higher military temperature specifications.

5. The researcher did not spend significant effort in miniaturization. The resulting prototypes, while not truly miniature, could operate in most applications.
6. No tests were reported to show that the power level was reduced by 30 to 50 percent on demand.

This project did not prove the feasibility of a snap-in load shed device. The researcher focused on screw-in devices made with commercially available components. The Lighting Research Center had developed an appropriate dimming circuit that was used in this project. Therefore the researcher focused his work on the alternate powerline communications equipment that was commercially available at the time of the project. At that time there was no set of components available that could "miniaturize" this device. All detection circuits developed by the Lighting Research Center had been developed as part of a related project on load shedding of fluorescent lighting. As Californians replace incandescent lighting with fluorescent lighting, the potential market for the researched device becomes ever smaller.

Recommendations

This project covered several aspects of the problems of load-shedding for incandescent lighting via remote communications. The central focus of this project was power line communication (PLC). The program administrator recommends that any future work evaluate alternative communications schemes, not the load shedding device itself. The PLC protocol must be acceptable to utilities and end users. This area of technology is changing rapidly and may be quite different in future years than it was during this project.

The researcher should investigate interoperability of load-shedding devices with timers, dimmers, and other devices that a user may have installed in series with the incandescent bulb.

The program administrator also recommends a thorough market study of the lighting situation in California prior to any further work on load shedding devices for incandescent lighting. The rapidly changing lighting market may have little need for a device to reduce the level of incandescent lights as incandescent lighting becomes an ever smaller percentage of the lighting market.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research would be increased reliability of the California electricity system. If the proposed load shedding could be accomplished, an important tool for handling peak power crises could be at hand. Reliability would be improved because there would be fewer instances when power blackouts occur.

The researcher estimated one million incandescent units per year could be converted to use a load shedding device. With the rapid conversion of lighting in California from incandescent to fluorescent lighting, the market for such a device could be easily saturated. Also, it is less likely that people who retain incandescent lighting will be willing to add a device to each bulb no matter how low a price. Since the research does not have any plans to take a product of this type to market, significant delays may ensure before any market penetration is achieved.

2.10. Novel Approaches to Ignition Enhancement of Natural Gas Under Engine-Like Conditions

Awardee: University of Southern California
Principal Investigator: Fokion Egolfopoulos

Introduction

Distributed power plants utilizing reciprocating internal combustion (IC) engines fueled by natural gas (NG) have significant problems achieving strict environmental standards while efficiently producing electricity in the lean-burn mode. The problem is in the ignition of NG, consisting mostly of methane (CH_4), which among all hydrocarbon fuels is the most difficult one to ignite. The key issue that this research and development project targeted was enhancing NG ignition under lean engine burning through the use of catalytically derived hydrocarbons such as ethylene (C_2H_4) and acetylene (C_2H_2), produced from a portion of the same NG fuel source.

The benefit to California ratepayers of this technology is the lowering of power costs for distributed generation projects due to the higher efficiency of the IC engines running in lean-burn mode on NG, while reducing the exhaust emissions of nitrogen oxide (NO_x), unburned hydrocarbons and carbon monoxide (CO).

The advancement of science for this project lays in the use of the in situ-produced carbon (C_2) gases as ignition enhancers in place of more expensive hydrogen (H_2) gas. In the proposed process, a portion of the natural gas is routed through a catalyst where the direct conversion of methane into C_2 hydrocarbons (primarily C_2H_4 and ethane (C_2H_6)) by its oxidative coupling with oxygen (O_2), commonly known as oxidative coupling of methane (OCM), occurs. Then the mixture of NG and C_2 gases enter the IC engine where the enhanced combustion occurs.

Objectives

The goal of this project was to determine the feasibility of improving the combustibility of natural gas (NG) in an IC engine through the use of in-situ produced C_2 gases. The researchers established the following project objectives:

1. Demonstrate improved ignition characteristics compared to lean premixed NG by itself as determined by the resulting T (hot-gas temperature) and K (strain rate) variables when C_2H_6 and C_2H_4 are added to lean premixed NG.

2. Demonstrate that additive mixtures of C₂H₆ and C₂H₄ (typical of the product slate of catalytic direct methane activation) when added to lean premixed NG will result in improved ignition characteristics compared to lean premixed NG by itself as determined by the resulting hot-gas temperature (T) and strain rate (K) variables.
3. Identify a promising catalysts/reactor technology that is capable of obtaining a minimum 20 percent yield of the desired additives.
4. Show, from the data generated in this project, the projected capital cost of adding the proposed technology to an IC engine would not exceed \$100 per kilowatt (kW) capacity.

Outcomes

The following were the key technical outcomes of the project:

1. The researcher demonstrated that the additives C₂H₆ and C₂H₄ when independently added to lean premixed NG would result in improved ignition characteristics. The ignition temperature was lowered by up to 80 Kelvin when adding C₂H₆, and by up to 120 Kelvin when adding C₂H₄. Minimal ignition temperature changes were experienced when CO₂, CO, and H₂O were added, so these additives were deemed ineffective in improving ignition. C₂H₆ and C₂H₄ also had a significant effect upon ignition delay decrease, and a lowered flammability limit when added to CH₄. This outcome demonstrated that the first objective was met with respect to C₂H₄ and C₂H₆.
2. The researcher further demonstrated that mixtures of the products of the catalytic direct methane activation, when added to lean premixed NG, would result in improved ignition characteristics as compared to lean premixed NG by itself. Objective 2 was thus also met; the ignition temperature drop was significantly dropped and the ignition delay decrease was also significantly influenced by the products of the catalytic reactor.
3. A promising stable catalyst for oxidative methane coupling was identified and tested. The catalyst consisted of magnesium/sodium (Mg/Na₂) tungstate/silica (WO₄/SiO₂). Though the attained C₂ yields were somewhat lower than what is reported in the literature (near 20 percent), the catalyst was easy to prepare and was much more stable; the latter is very important for the unattended long-term life required for IC engine operation in remote locations. A novel membrane reactor technology using this catalyst was also studied; though this technology is more capital-intensive, its application can raise the attained yield to approximately 40 percent. Objective 3 was thus met.
4. Though it is difficult to provide accurate estimates without actual field testing of the technology, preliminary calculations based on the data generated in this project indicated that the projected capital cost of adding the proposed technology to an IC engine would not exceed \$100 per kilowatt (kW) capacity. The actual estimated cost was \$94.52 per kW for a 250 kW engine. Thus Objective 4 was also met.

Conclusions

The key conclusions are:

1. Experimental results show that the addition of C₂ components to natural gas has the effect on enhancing ignition characteristics, while common by-products of OCM, such as CO, CO₂, and H₂O have minimal effects on the tested parameters. Ethylene (C₂H₄) was

shown to be more effective than ethane (C_2H_6) at enhancing the ignition characteristics of NG. Thus, among the various products of OCM, C_2H_4 is the most desirable regarding ignition.

2. Experimental results show that coupling an OCM reactor and a practical combustor results in the enhancement of its ignition characteristics. The lower adiabatic temperatures of approximately 30 degrees Celsius are relatively modest, accompanied by lowering the rate of NOx production by approximately 15 percent. Integrated reaction pathway analysis has yielded valuable insights into the combustion mechanism and explains the enhanced ignition of methane/air mixtures due to C_2H_4 and C_2H_6 additives.
3. An extensive literature search was conducted to locate an appropriate catalyst. Experiments with the selected catalyst, $Mn/Na_2WO_4/SiO_2$, have shown it to be stable over long periods of usage while obtaining 15 percent yield. Combustion simulations have shown 15 percent yield to be sufficient for enhancing the ignition propensity of natural gas.
4. Preliminary economic analysis of the catalysis synthesis and reactor costs show that integration of the completed unit could be achieved for a cost of \$94.52 per kW, which is less than \$100 per kW limit.

In general the authors achieved their objectives in demonstrating that the addition of C_2 gases to NG improves the ignition characteristics, i.e. lowered ignition temperature and improved efficiency and lowered NOx emissions. However, the estimated costs of approximately \$25,000 for a 250 kW engine-generator are excessive for the modest improvements attained. The most valuable results of this project are in the detailed experimental and theoretical studies that provide a valuable addition to literature on the basic understanding of ignition processes involving NG and C_2 -HC.

Recommendations

The use of oxidative coupling of methane (OCM) for the in-situ production of C_2 hydrocarbon in ignition enhancement during lean combustion of methane was proven technically feasible. In order to bring the technology to the commercial stage the following tasks should be conducted:

1. Determine the ignition characteristics with realistic natural gas mixtures and practical combustors to evaluate the practical benefits of the process.
2. Study the long-term catalyst performance of OCM reactions.
3. Carry out an extensive economic evaluation of the technology, including a detailed market survey.
4. Develop a bench-scale prototype to study the effects of the proposed coupling on practical devices. Cycle to cycle variations of the engine and relevant control mechanisms for the reactor should be investigated in this stage.
5. Study the effect of inlet NG concentrations on the reactor performance to determine if additional control parameters should be implemented.
6. Investigate the possible use of the proposed technology with an emerging energy production technology, such as homogeneous charge compression ignition (HCCI).

Even though the above recommendations would add to the knowledge base for this ignition technology, it is still not clear whether the improvements in efficiency and lower NOx emissions are justified by the added expense of the catalyst and associated combustion equipment. In other words, this technology could be a long way from the marketplace. The most important of the above recommendations are numbers 2 and 3 dealing with lifetime of the catalyst and economics of the process.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow on funding within the PIER Program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply. This is accomplished by the improved exhaust emissions and efficiency of an IC engine when using NG as fuel with added C₂ hydrocarbons. Due to improved engine efficiency, the cost of electricity may be lowered. The overall cost of the technology, about \$100 per kW, could be amortized in 10,000 hours to achieve a cost addition of \$.01 per kWh. This cost could be offset by the reduced fuel use. However, these benefit statements are somewhat speculative and need to be verified in a field test.

2.11. A Dynamic Ceiling for Improved Comfort With Evaporative Cooling

Awardee: Steve Winter Associates, Inc.
Principal Investigator: Dianne Griffiths

Introduction

Residential air conditioning is a major contributor to summer electricity use and peak electricity demand in California. In the dry western climates, where new home construction is increasing, evaporative cooling offers energy and peak demand reductions compared to vapor compression air conditioning. However, evaporative cooling cannot maintain adequate occupant comfort conditions in many California locations. Poor circulation throughout a house has been a major barrier that plagues this alternative cooling strategy and has hindered its greater implementation. Enhancing indirect evaporative cooling technology, which is an indirect evaporative cooling technique for cooling conditioned air with a heat exchanger and an evaporative cooled process air stream, with dynamic ceiling construction could achieve cooling comfort with successful use of ductwork designed for conditions of severe summer California weather. In the past, evaporative cooling has generally been unsuccessful on peak design days for hot arid climates. Envelope upgrades coupled with indirect evaporative cooling will enhance hot day comfort levels, hastening the adoption of this energy saving and demand reducing technology in California. This technology could have widespread applicability to new single family home construction.

There are approximately 150,000 new single family homes constructed in California each year. With a 10 percent adoption rate, the first year electricity savings would be 8,700 megawatt hours (MWh) and the demand reduction would be 45 megawatts (MW). This is based on an average energy savings estimate of 580 kilowatt hours (kWh) per home (58 percent reduction in cooling energy requirements) and a 3 kilowatt (kW) demand reduction per home. After 10 years, the annual energy savings will have grown to 87,000 MWh, and the demand reduction will have reached 450 MW. Using an average cost of energy at \$0.105 per kWh and an avoided capacity value of \$50 per kW per year, annual energy cost savings are projected to be \$30 million after 10 years of market adoption.

The concept integrates dynamic ceilings with indirect evaporative cooling in a new configuration. The development of innovative comfort solutions to make evaporative cooling more viable offers an excellent potential return on investment due to the energy and peak demand savings associated with an increase in the market penetration of this non-compressive cooling system. A cost effective alternative to electric vapor compression technology could provide much needed demand side relief on California's energy grid, and innovations in this sector could reduce grid power usage. With a major portion of new homes being developed in dry inland areas, evaporative cooling is an attractive solution to energy and peak demand reductions. Ceiling heat gain may be eliminated if a portion of the conditioned air, normally exhausted, passes through dynamic ceiling insulation before finally being expelled to a vented attic. The comfort improvements associated with integrating evaporative coolers with the

buildings that they cool in this manner will be greatest during peak design conditions. A furred dynamic ceiling design has been developed with a small number of controlled pressure relief dampers that allows house air to be exhausted through attic insulation and eliminates ceiling heat gain. Comfort will be further improved by locating dynamic ceiling dampers around the perimeter of a house above windows, resulting in a more even distribution of cooled air throughout a house.

Objectives

The goal of this project was to determine the feasibility of reducing peak cooling loads as well as increasing design day comfort in residences utilizing indirect evaporative cooling in concert with a dynamic building envelope. The researchers established the following project objectives:

1. Fabricate a test cell capable of testing the performance of the proposed dynamic ceiling and wall designs.
2. Demonstrate with physical testing that the proposed dynamic ceiling and wall designs are capable of maintaining interior surfaces at indoor air temperature when attic air temperature is 130 degrees Fahrenheit.
3. Develop and validate an airflow model for dynamic ceiling performance that predicts airflow rates for various dynamic ceiling configurations.
4. Construct a model that simulates the energy performance of a house with evaporative cooling and a dynamic envelope during design day conditions.
5. Use the United States Department of Energy model (DOE-2) to determine whether houses built in California with evaporative cooling and a dynamic envelope can maintain thermal comfort comparable or better than conventional houses that use compressive air conditioning.
6. Refine dynamic ceiling plenum design for lower material and installation cost, and for compatibility with conventional attic insulation alternatives.
7. Develop and fabricate the dynamic ceiling intake damper.
8. Confirm that the proposed dynamic envelope design complies with all relevant California building codes.
9. Develop preliminary design guidelines that could be used to test the concept in a full-scale prototype house.
10. Estimate incremental costs of building a house with evaporative cooling and a dynamic envelope compared to a conventional Title 24-compliant house using compressive air conditioning.

Outcomes

1. A test chamber was constructed that is capable of subjecting an 8-foot by 8-foot dynamic ceiling system to peak summer attic conditions. A dynamic ceiling system, based on a refined design, as was constructed for use in the test chamber.
2. Results from this test chamber demonstrate that a dynamic ceiling system can maintain ceiling drywall at room temperature during design conditions, eliminating ceiling heat

gain. The measured relationship between airflow rate through the dynamic ceiling and heat gain eliminated matched the analytical model. Minimum airflow is substantially less than that available from an evaporative cooler.

3. An airflow model was constructed that simulated the energy performance of the dynamic envelope.
4. A model of a minimally Title 24-compliant Sacramento house cooled by an indirect-direct evaporative cooler was developed. Sacramento conditions are indicative of California design days, and the simulation in the model could be accurately tested.
5. Based on the results of an hourly whole building energy simulation, the complete elimination of ceiling heat gain due to a dynamic ceiling was found to reduce peak cooling load by 17 to 25 percent during design conditions and significantly improve comfort.
6. A revised, more straightforward, dynamic ceiling design was developed that is compatible with either fiberglass batt or loose fill attic insulation.
7. A prototype dynamic ceiling damper was designed, constructed, and tested in a laboratory bench top setting. The damper can be sealed with a magnetic register cover in the winter to cut heat losses.
8. The refined dynamic ceiling system design complies with the International Residential Code, International Energy Conservation Code, and relevant National Fire Protection Association standards.
9. The finalized dynamic ceiling design and intake dampers were integrated with an indirect-direct evaporative cooler in a prototype house. In addition to reducing peak cooling load, the dynamic ceiling design aided in the circulation of conditioned air, improving occupant comfort and market acceptance.
10. Material and labor costs associated with the dynamic ceiling system design were estimated based on prototype house experience. The incremental cost was estimated of a house with a dynamic ceiling integrated with a high performance evaporative cooler compared to a house with a conventional seasonal energy efficiency ratio (SEER) 10 split air conditioning system.

Conclusions

1. The test chamber proved to be an accurate method of creating temperature conditions typical for hot, arid climates. The wall/ceiling test section was an adequate size for testing the dynamic ceiling system and made clear where refinements had to be made in the assembly of the system.
2. Where the ratio of the temperature difference across an insulator and the heat flow per unit area through it is measured by a R value, experimental and analytical findings showed that the minimum airflow rate required to eliminate R-38 ceiling heat gain is approximately 25 percent the airflow supplied to a house by a typical evaporative cooler.

3. An analytical expression for the rate of airflow through a dynamic ceiling system as a function of room pressure was developed and validated based on test chamber measurements.
4. The modeling results of a minimal Title 24-compliant Sacramento house cooled by an indirect-direct evaporative cooler showed favorable comfort and energy savings findings.
5. Modeling and bench scale testing results showed that indirect evaporative cooling in a dynamic envelope is capable of achieving thermal comfort comparable to conventional houses using compressive air conditioning. Results showing an hourly building energy simulation proved that the complete elimination of ceiling heat gain is possible with a dynamic ceiling.
6. Economical dynamic ceiling designs are feasible that are compatible with contemporary insulation materials.
7. The prototype damper was designed to be compatible with a standard return air grille and is easily installed by contractors. Other damper designs should be encouraged to ensure optimal performance and homeowner acceptance.
8. The refined dynamic ceiling system design complies with many of the codes that make the industry standard. However, smaller governing codes can be more stringent and should be investigated in future phases.
9. This enhanced air distribution benefit is relevant to improving occupant thermal comfort and market acceptance. Additional testing is required to ensure longer term performance.
10. A preliminary assessment of incremental costs of the dynamic ceiling with indirect evaporative cooling suggests \$ 0.60 per square foot is a reasonable target price adder. This is comparable to the incentive levels established for houses using evaporative cooling in some California utility territories. However, material and labor costs that were assumed in the can vary greatly and thus a spectrum of costs should be analyzed. This can show whether the incremental cost can make this concept more feasible in certain areas than others.

Laboratory testing demonstrated the technical feasibility of integrating a dynamic ceiling with an indirect evaporative cooler in new residential homes. The dynamic ceiling suppresses heat gain enabling indirect evaporative cooling to achieve comfort even on unseasonably hot days. Whole house energy simulations indicate a reduction in peak cooling load by 17 to 25 percent. In addition, controlled ceiling dampers distributed in different rooms will aid in the circulation of evaporative cooled air throughout the house. The combined thermal comfort improvements of this system will support greater market acceptance of evaporative cooling. Incremental costs are modest and in the same range as incentives being offered by some California utilities.

Recommendations

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the

program administrator has determined that the proposed technology should be considered for follow on funding within the PIER Program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

A dynamic ceiling system that improves comfort in evaporative cooled houses is an innovative idea in early stages of development. Future work should focus on:

- Finding the most appropriate near-term applications for the dynamic ceiling system and identifying commercialization needs.
- Automatic damper designs should be evaluated for cool winter climate regions that minimize the winter penalty without occupant intervention.
- Involve a ventilation product manufacturer to fabricate the refined ceiling dampers.
- Involve a California home builder to implement a second prototype dynamic ceiling that serves inland California. Performance should be monitored for a full year to analyze the long-term effect of the systems over the different seasons. Summer peak cooling demand savings should be quantified and occupant interviews should be conducted to find out the success of the new damper system.
- Results from prototype houses should be communicated to the housing industry and to prospective home buyers to hasten adoption of the technology.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. At a 10 percent adoption rate for new California single family homes over a 10-year period, the annual reduction in energy usage, associated costs and emissions is summarized as follows:

- Energy 87,000 MWh reduction
- Demand 450 MW reduction
- Cost savings \$30 million
- CO₂ 33,000 tons reduction
- NOx 5,250 lbs reduction (Assumes 0.07 lb per MWh site energy reduction)

Occupants could experience improved indoor air quality due to the high ventilation rate caused by the operation of the evaporative cooling system. Improved air quality is also possible due to the large volume of air infiltrating through the envelope that will carry away accumulated moisture in the walls and ceilings.

There would be an increase in water consumption with evaporative cooling. The estimated water use per unit varies but is on the order of 10,000 gallons per year. After 10 years of technology adoption at the rate of 15,000 units per year, the water use impact would be 1.5 billion gallons (4,500 acre-feet) annually. This usage is small compared to California's total water consumption of 9.5 million acre-feet per year. At \$3 per 1,000 gallons, the economic cost to evaporative cooling users is \$4.5 million each year (\$30 per unit).

2.12. Integrating Evaporative Cooling With Dynamic Insulation for Occupant Thermal Comfort

Awardee: Thermochem, Inc.
Principal Investigator: Diane Griffiths

Introduction

Geothermal production of electricity is an important renewable energy technology in California. Significant development of geothermal has occurred over the years, and geothermal is one of the most mature and most reliable of the renewable energy technologies. Geothermal resources, including the "dry-steam resource at the Geysers area contain contaminants that are corrosive to piping systems, power plant equipment or otherwise threatening to plant reliability and/or the environment. Removing these compounds from the resource stream using traditional measures reduces the fluid temperature (or steam quality) and hence plant efficiency. These compounds include various acidic chemicals including hydrochloric acid (HCl.)

In the traditional process for removing corrosive chemicals, called a corrosion mitigation facility (CMF), water and sodium hydroxide are pumped into the steam to absorb and neutralize HCl. By combining the resulting wet steam from each CMF, the temperature (steam quality) in the entire gathering system is reduced. Severe corrosion can occur when the steam from relatively low HCl-producing wells, which previously did not require treatment due to their high steam temperature, mixes with the wet CMF steam. This creates a situation where more wells require scrubbing to prevent gathering system corrosion. The plants at the Geysers have suffered from this problem for years, with weekly corrosion failures occurring in the pipelines.

A process was developed, termed dry steam scrubbing (DSS), which removes corrosive HCl from geothermal steam without reducing the steam temperature. By keeping the steam at the maximum temperature possible and free of moisture, corrosion throughout the steam gathering pipelines is minimized. The DSS process uses dry calcium carbonate (calcite) pellets as the absorbing media for HCl. By removing HCl through the DSS process, without heat loss, this problem should be minimized or eliminated.

Objectives

The overall goal of this project was to demonstrate the feasibility of dry steam-scrubbing technology. The researcher established the following objectives:

1. Upgrade an existing pilot plant (to demonstrate the DSS system).
2. Fabricate prototype calcite bed configurations.
3. Demonstrate a calcite bed is capable of removing at least 95 percent of HCl.
4. Demonstrate that the DSS process does not reduce the temperature more than 10 degrees Fahrenheit
5. Demonstrate that the DSS process does not cause pressure drop greater than 15 pounds per square inch (lb/psi).
6. Demonstrate that 1 to 5 parts per million (ppm) of residual HCl remaining in the steam after treatment by the DSS process does not require further corrosion mitigation.
7. Confirm that DSS vessels can be approximately the same size as conventional separators.
8. Confirm that a 400 kilometers per hour (kph) steam flow containing 30 ppm can be treated at a cost of approximately \$2,500 per month with a DSS system

Outcomes

1. The existing pilot plant used for the initial Department of Energy funded research was modified and upgraded to meet the requirements of the calcite bed tests.
2. Three different prototype calcite bed configurations were designed and tested. The second bed was determined to be optimal and the best candidate for full-scale testing. It was not necessary to test 8 beds as originally proposed.
3. It was demonstrated that the calcite bed DSS process is capable of removing up to 98 percent of HCl from superheated steam.
4. It was demonstrated that the calcite bed DSS process will reduce the steam superheat temperature by less than 10° Fahrenheit with adequate insulation.
5. It was demonstrated that the calcite bed DSS process does not cause a pressure drop greater than 15 psi.
6. It was demonstrated that the calcite bed DSS process will result in about 1 to 3 ppm of residual HCl remaining in the steam. It was determined from other field data generated at The Geysers that this amount of HCl does not require further corrosion mitigation provided that the steam is superheated by at least 40° Fahrenheit.
7. It has been confirmed that DSS vessels can be approximately the same size as water/caustic scrubbing separators.
8. It has been confirmed that a 400 kph steam flow containing 30 ppm can be treated at a cost of approximately \$2,500 per month with a DSS system.

Conclusions

It was demonstrated that up to 160 ppm HCl could be effectively treated by the DSS process. Wells producing 50 ppm or more HCl are conservatively estimated to need a calcite bed depth of 72 inches. The first full-scale DSS vessel was designed to accommodate a bed depth up to 96 inches. Changing the bed depth to optimize chloride removal and to minimize pressure drop is a simple matter of adding or removing calcite pellets.

Reflux regeneration was determined to be the most effective means to remove reaction products from the calcite bed and maintain performance. This is accomplished by shutting-in the outlet pipe from the vessel for several hours while leaving the inlet open and the drain valve partially open. Regeneration about every 30 days maintains the outlet chloride at a constant level.

The chloride concentration can be reduced down to about 2 ppm (plus/minus 1 ppm), regardless of the inlet chloride over the range of 6 to 160 ppm. This will be sufficient to prevent corrosion in the gathering system under most circumstances. The steam temperature will increase in sections of the gathering system where DSS replaces the CMF process. The mitigation of general gathering system corrosion by reducing HCl from high-chloride wells while maintaining superheat is the greatest advantage of the DSS process over the current CMF technology.

The operating cost of the DSS process, based on chemical usage alone, is about one half the cost of the conventional CMF process. The capital cost of the DSS process is expected to be the same or less than the CMF process, depending on the number of vessels required.

Recommendations

A full-scale DSS system should be tested to confirm operating parameters and make any fine-tuning adjustments to the process and vessel design, relative to steam conditions at Geysers. Flow parameters should be tested under varying conditions in order to establish design and operating nomographs for application to other steam and contaminant conditions, especially for export markets. Computational fluid dynamic modeling of flow regimes within the calcite bed should be conducted to determine localized flow patterns, in order to optimize bed design (e.g. mixed particle size, stacked particle sizes, pore sizes, etcetera.) Finally CFD and chemical kinetics modeling should be undertaken to determine localized exothermic levels of reactants within the bed and used to protect against localized hot-spot which could degrade bed integrity. The calcite-based DSS should be tested on other acidic (e.g. sulfuric) components existing in geothermal resources outside the Geysers.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow on funding within the PIER Program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to California of this research is from reduced environmental impacts of the electricity supply system. Secondary benefits include increased reliability of the supply system. The DSS process could provide an immediate benefit to the California Renewable Energy Market, primarily at The Geysers, which is the largest steam-dominated geothermal field in the world. This field produces steam for 21 power plants with a combined generation of 900 megawatts. The DSS process may help mitigate widespread corrosion problems throughout the steam gathering system and power plants, which causes intermittent shutdowns for repairs and reduces the useful life of pipelines and power plant equipment. Therefore, this new technology should increase the reliability, extend the life, and reduce the cost of renewable, base-load geothermal power for California. The DSS process is also an exportable renewable energy technology for California-based geothermal engineering and consulting firms.

The researchers estimate that the installation of a DSS system on a single well at The Geysers is expected to eliminate 4 outages per year, totaling 12 hours each, due to corrosion failures caused by CMF steam mixing with superheated steam from other wells feeding the same collection pipeline. The intermittent shutdown of the wells feeding this pipeline results in the loss of 576,000 kilowatt hours of power per year, or \$37,000 in electric sales. The corrosion damage repair cost is \$15,000 per year. The payback for installation of the DSS system is three (3) years, with a cumulative pre-tax cash flow of \$407,500 after 10 years.

2.13. A Low-NOx Porous Ceramics Burner Performance Study

Awardee: Florida Institute of Technology
Principal Investigator: Pei-feng Hsu

Introduction

Air quality is a major issue in California's agricultural areas. The California Legislature required the state Air Resources Board (ARB) to investigate air-emission abatement equipment required by the San Joaquin Valley Unified Air Pollution Control District. ARB prepared a one-time report to the Legislature describing its findings. The report showed that sources in the food-processing industry account for 0.5 percent of the total nitrogen oxide (NO_x) emissions inventory in the valley. However, the impact of these NO_x emissions on the region's air quality

is disproportionately significant during the food-processing season, which occurs during July, August, and September. Typically, those are the months when the air quality is the worst. The ARB identified boilers and continuous dryers as the equipment generating the emissions in the food industry. The San Joaquin Valley has been reclassified to “severe” for non-attainment of the federal, health-based standards for ozone. This has caused the local district to seek further reductions in NO_x emissions, a precursor to ozone. These new reductions apply to the seasonal food-processing industry. Boilers used in other industries throughout California contribute to air pollution in metropolitan areas.

Significant reductions in pollutant emissions from several classes of equipment have not kept pace with the increasing use of energy in California. Thus, air basins such as the San Joaquin Valley are experiencing degraded air quality. The California Air Resources Board is identifying significant polluters and taking action to control those sources. Boilers, used extensively in the food industry, are noted contributors to air pollution. If boiler NO_x emissions were reduced from the current level of 30 parts per million, volumetric dry (ppmvd) to 9 or 3 ppmvd, some of the air problems in the San Joaquin Valley would abate. This would lead to a healthier climate for all of the residents.

Porous radiant burners are now in use in industrial and commercial applications because of their excellent performance characteristics, specifically, low pollutant emissions, high turn-down ratios, and more efficient radiation-heat output than the conventional free-flame burners. In this project, the researcher proposed development of porous ceramic burners for use in industrial and food industry boilers. The porous or reticulated ceramic can be characterized as rigid, porous, and sponge-like in appearance. The reticulated ceramic burners can operate at much higher temperatures (near 1,665 degrees Celsius) than the fibrous burners currently utilized (near 982 degrees Celsius). However, the ceramic burners are susceptible to thermal shock and are not yet available in the market.

The goal of this project was to demonstrate that porous ceramic burners would provide greater heat release with lower emissions than porous radiant burners. When this project was started, only one-dimensional, flat, reticulated ceramic burners had been studied. Industrial boilers require more practical cylindrical burners. The researcher proposed developing a dual-layer, cylindrical, reticulated ceramic burner with a stable flame to characterize its emissions and thermal characteristics. Earlier work by the researcher had shown that the dual-layer structure displayed favorable flame stability.

Objectives

The goal of this project was to determine the feasibility of multi-layer, cylindrical-shaped, porous ceramic burners to reduce emissions while increasing heat release. The researcher established the following project objectives:

1. Fabricate and test prototype two-layer and three-layer cylindrical-shaped, porous ceramic burners.
2. Demonstrate NO_x emissions below the current, best-available control technology of 0.076 pounds per megawatt-hour (lb/MWh) or 9 to 12 parts per million, volume dry

3. Demonstrate porous ceramic burners with a radiant heat output 25 percent more efficient than that of free-flame burners.
4. Demonstrate that the prototype, multi-layer porous ceramic burners increase combustion stability resulting in extension of the lean flammability limit as compared to current ceramic fiber mat burners.

Outcomes

1. The researcher designed, fabricated, and tested a dual-layer cylindrical burner to determine its combustion performance. A stable flame was established inside the reticulated ceramic cylinder and low emissions were noted. However, the fuel/air-mixture-distribution tube inside the cylinder center cavity melted in the middle of the experiment due to high temperature. The researcher tested equivalence ratios of 0.7, 0.75, and 0.8. The flame speed ranged from 22.5 to 65 centimeters per second (cm/s).
2. Higher flame speeds produced greater levels of NO_x and CO. At lower flame speeds, the dual-layer porous ceramic burners were capable of reducing NO_x emissions below the current, best-available control technology of 0.076 lb/MWh (or 9 to 12 ppmvd corrected at 3 percent O₂). At higher flame speeds or firing rates, the ceramic cylinder burner did not meet the 2007 California Air Resources Board emissions mandate for distributed-generation systems (approximately 9 to 12 ppmvd).
3. The burner in this study displayed an average 45 percent radiation efficiency over a wide flame-speed range at the equivalence ratio of 0.9. The radiation-heat output increased with firing rate.
4. Increased combustion stability could not be determined because of the severely limited life of the distribution tubes. There was no determination of increased lean limit on the reticulated ceramic burners.
5. The researcher compared the cost of reticulated ceramic burner material to the price of a commercially available fibrous burner of a typical size. For a commercial fibrous burner rated at a heating capacity of 400 boiler horsepower, the fibrous burner has a price of approximately \$10,000 to \$12,000. For the same heating capacity, the reticulated yttria zirconia (YZA) burner has a projected cost of \$6,300.

Conclusions

1. The researcher speculated the burner geometry was responsible for the failures. The researcher first tried material substitution by fabricating distribution tubes from several high-temperature alloy materials, but that was not successful. It is possible that the distribution tube is failing from flashback. The cylindrical ceramic tube may be acting as a black body and radiating excessive thermal energy to the distribution tube.
2. Limited amounts of emission data were obtained in a stable flame situation. Results showed emissions lower than 2007 standards at some operating conditions. It is not clear if the range of low-emission operation is sufficient for commercial boiler burners. A possible solution is to reduce the combustion temperature to the level of the fibrous

burners, i.e., about 1,000 degrees Celsius, to reduce the thermal NO_x formation. Reduction of combustion temperature would reduce emission at the cost of lowering the thermal radiation available from the burner.

3. The data from a commercial fibrous ceramic burner indicated that at 0.9 equivalence ratio and with the firing rate of 211.3 kilowatts per square meter (kW/m²) the highest radiation efficiency was 38.4 percent. Therefore, the radiation efficiency of the ceramic burner is 17 percent higher than that of the fibrous burner. Both the reticulated and the fibrous burners have significantly higher radiation efficiency than that of the conventional free-flame burner. Thus the reticulated burner meets the goal of greater than 25 percent radiation efficiency than a free-flame burner.
4. This objective was not met.
5. While the cost estimate for the reticulated burner is significantly lower than the price mentioned for the fibrous burner, it may not include manufacturer margins for overhead costs and dealer markups. Considering that the reticulated ceramic burners have higher operating temperature, higher radiation efficiency, and about the same level of pollutants emissions as the fibrous burners, the reticulated ceramic burners may have a large market potential if the problem of thermal strength can be solved.
6. Both reticulated materials tested, partially stabilized zirconia (PSZ) and YZA, could not sustain the high temperature cycling needed for industrial boilers. Ceramic manufacturers must solve the problem of thermal strength in porous ceramics before this burner concept can be a commercial success.

Recommendations

The researcher pursued an avenue of research that could lead to significant ratepayer benefits if the feasibility were proven and a commercial product produced. While the technical work in this project was competent, the feasibility is still questionable due to unforeseen material problems. Until reticulated ceramic materials with higher thermal strength are commercially available, the utility of this innovation is limited. Thus, it is difficult to recommend further research in cylindrical, reticulated ceramic burners until new materials are developed. In addition, the repeated failure of the distribution tube must be addressed prior to commercialization. The program administrator considers the distribution-tube failure resolvable through design without material innovation.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research reduced environmental impacts of the California electricity supply. If the reticulated ceramic burner were available to California industries such as food processors, air emissions could decline. This is particularly important in the San Joaquin Valley, an area both of numerous food processors and of severe air emissions. Because it was difficult to fully characterize the cylindrical, reticulated ceramic burner, it is not possible to accurately assess the potential benefits of this innovation to California ratepayers. Further work must be accomplished to determine if this innovation can operate at both high thermal efficiency and low NOx emissions. Commercially available fibrous radiant burners can achieve NOx emission levels of 9 ppmvd at 3 percent oxygen with reasonably high thermal efficiency. The innovation in this project holds the potential of increasing thermal efficiency further while achieving the same low emission levels.

2.14. Plastic Solar Cell

Awardee: Nanosolar
Principal Investigator: Brian Sager

Introduction

To promote the use of renewable energy sources, the California Legislature passed Senate Bill 1078 (Sher, Chapter 516, Statutes of 2002) (SB 1078). It was signed into law in 2002. SB 1078 requires that California electric utilities increase procurement of electricity from renewable energy sources until these sources supply at least 20 percent of utility retail energy sales. When implemented, this legislation will reduce the consumption of carbon-based fuels by utilities and their suppliers. A distributed renewable-resource generating capability would also reduce the need for new utility-scale generating plants and related transmission lines. A rooftop photovoltaic (PV) system provides maximum power in the afternoon, nearly coincident with the peak demand for air conditioning. Any excess energy generated by the PV can be exported to the grid to reduce imbalance between peak electric demand and available supply in that region of the state. The barrier to wider use of PV generation of electricity has been the high initial cost of the predominant crystalline-silicon solar modules. Currently, these modules account for 93 percent of the PV market.

A flexible, plastic-film-based PV made by economical printing and roll-to-roll processing could offer many advantages, including lower material and manufacturing costs. Efforts to construct inexpensive plastic PV cells have adopted a random microstructure. Such approaches, however, have been ineffectual because the photo-excited carriers have short lifetimes but must diffuse long path lengths before collection, resulting in a low power efficiency of 1 to 2 percent. An efficiency of 5 to 10 percent is necessary to lower their capacity cost and to reduce the physical area required for solar panels. This project examined an improved microstructure that offered shorter diffusion lengths and higher efficiency.

In today's dominant technology of crystalline-silicon production, PV modules have a retail capacity cost as low as \$3.41 per watt peak (W_p), with an average, single-module retail cost of \$5.12 per W_p (2005). This price is based on the purchase of single solar modules and is exclusive of sales taxes. (The photovoltaic industry has established a 2010 industry cost goal of \$1.50 per W_p for PV modules, to make PV broadly competitive in the residential market without subsidies). The researchers projected that plastic PV panels could have a materials cost as little as \$23 per square meter compared to present-day costs of \$300 to \$400 per square meter for crystalline silicon materials. This comparison was based on both units having approximately the same efficiency. The project estimated a cost for electricity generated with plastic PV panels at less than \$0.10 per kilowatt hour (kWh). This would make it competitive with today's cost of utility-generated electricity of \$0.125 per kWh (2002 weighted average.) and \$0.121 per kWh (2005 forecast weighted average.). Advantages of a renewable-powered generating capacity competitive in today's cost structure include the reduced production of nitrogen oxide (NO_x), sulphur oxide (SO_x), and carbon dioxide (CO₂) and, importantly, lower exposure to future increases in the cost of carbon-based fuels.

To make plastic PV solar cells cost effective requires an increase in their efficiency. The efficiency is limited by a short diffusion length of the excited charge carriers and the long paths present in existing designs. The scientific advance required to solve the problem of short diffusion lengths and long paths is to adopt a nanoscale, charge-splitting network in a PV cell by structuring a regularly arranged, straight-channel, mesoporous grid of electron-accepting material. The pores in this electron-accepting material are interpenetrated by an organic, hole-accepting material. Sol-gel chemistry permits the creation of a self-assembling titania (TiO_2) nanostructure with uniformly spaced and sized pores. The average channel diameter can be set from 2 nanometers (nm) to more than 10 nm. Filling these pores with a light-absorbing organic creates a hybrid, organic-inorganic, charge-splitting network.

In a PV cell the titania grid is deposited on a substrate with an electrically conducting coating with which it does not make good electrical contact. The hole-accepting pore material does make good electrical contact with the substrate. A special transparent conducting film is deposited on top of the cell establishing contact to the titania. In operation, light passes through the top electrode into the light-absorbing organic material, where it creates pairs of electron-and-hole charge carriers. The charge carriers split at the organic-titania interface; the excited holes diffuse through the hole-accepting organic to the bottom electrode, and excited electrons diffuse through the titania to the top electrode. The nanoscale periodicity of this array can closely match the diffusion length of the excited carrier, allowing for more efficient charge splitting and providing for improved charge collection. Finally, such a fabrication technology must scale up to large-surface-area fabrication using low-cost, high-volume, web-coating processes.

Objectives

The goal of this project is to determine the feasibility of producing a plastic solar cell in which the charge-splitting network of the active layer of the device is constructed using a self-assembling mesoporous film. The researchers established the following project objectives:

1. Fabricate a prototype, 1 centimeter (cm) \times 1 cm, bench-scale, nanostructured photovoltaic cell.
2. Demonstrate the capability of producing a uniform nanostructured film with evenly spaced pores 10 to 12 nm apart, 10 to 12 nm in diameter, and 70 to 100 nm in pore length.
3. Demonstrate a polychromatic conversion efficiency of 2 percent in an area of 1 cm \times 1 cm.
4. Demonstrate optoelectronic stability of 80 percent upon a 2-month exposure to sunlight.
5. Show from the data generated in this project that the projected materials cost continues to be less than \$40 per square meter at the cell level for the proposed plastic solar cell.

Outcomes

1. The project successfully fabricated at least one working prototype, 1 cm \times 1 cm, bench-scale, nano-structured PV cell. Its fabrication is described in narrative form. No photographs of the device are presented.

2. Formation of nanostructured films (nanotemplates) composed of titania was carried out using sol-gel chemistry. This technique produces uniformly spaced and sized nanotemplates with an average channel diameter typically set within a range from 2 to 10 nm. The researchers report that they succeeded in creating uniform films with pores evenly spaced at intervals of less than 10 nm, and that they achieved target dimensions for the pore structures (5 to 10 nm diameter x 70 to 100 nm pore length), as well as a range of other aspect ratios and sizes. They found that pore-swelling agents could extend the range of channel periodicity from 10 nm to more than 30 nm. Little data are presented beyond the narrative in support of these outcomes.
3. An air mass 1.5 power-conversion efficiency of 2.7 percent was calculated from the measurements after normalizing for light absorption and reflection in the top semi-transparent electrode.
4. The researchers did not present data on long-term testing under illumination. They did report that power-conversion-efficiency levels were not stable in air (photocurrent and voltage both decayed on the time scale of seconds). They attributed this to the absence of encapsulation. Additionally, they suggested that photo-catalyzed degradation of active organic filler material by titania is present.
5. Data on projected materials cost was not presented, nor any demonstrating the continued support of a projected materials cost of \$40 per square meter at the cell level.

Conclusions

1. At least one working prototype, 1 cm x 1 cm, bench-scale, nanostructured, photovoltaic cell was fully fabricated and shown to produce electrical power. This result validated the approach based on three-dimensional nanostructured films as templates for the organic active medium.
2. The technique of sol-gel chemistry for the titania-film nanotemplates proved valid. It appears to offer adequate control over uniform pore diameter, spacing, and depth. The researchers reported that pore-swelling agents could extend the range of channel periodicity from 10 nm to more than 30 nm, but they did not provide useful details. Importantly, these pore structures proved capable of filling with organic active material and the successful application of contacts. Overall, the narrative presents little additional data in support of these outcomes, but the objective appears to have been substantially met.
3. The power-conversion-efficiency goal for this project was 2 percent for a prototype cell. Functional analyses of the first, complete prototype cell with a semi-transparent, thin-film, gold-metal, top electrode (which was 40 percent transmissive) gave a calculated efficiency of 2.7 percent after normalizing for light absorption. Apparently, a large correction factor of 2.5 has been applied to the data. The researchers should have supplied more details or discussion of this correction and some discussion of what might constitute a truly transparent top electrode.
4. No data addressed long-term testing under illumination; therefore, this objective remains unmet. The researchers did report that power-conversion-efficiency levels were not stable in air in the absence of encapsulation (photocurrent and voltage arising from

un-encapsulated devices both decayed on the time scale of seconds), but they supplied no data to explain this. They also speculated that photo-catalyzed degradation of organic materials by titania is present but do not explain if this degradation is in addition to the inferred reaction with air.

5. The objective of showing the continuing support of the projected materials cost of \$40 per square meter at the cell level remains unmet. While it is not possible to predict a cost from the information provided, one can infer from the relatively small amounts of materials employed that the cost could be low in mass production.

Overall, the main goal of this project was “to determine the feasibility of producing a plastic solar cell in which the charge-splitting network of the active layer of the device is constructed using a self-assembling, mesoporous film.” The project did achieve this main goal by growing a self-assembling mesoporous film, demonstrating a working solar cell, and meeting the first three of the five objectives.

Recommendations

Evidently, the researchers have concluded that titania must be dropped as a material for a nanoscale, charge-splitting network in a PV cell for two reasons: 1) It absorbs only the highest few percent of energy in the solar spectrum, and 2) the part of the spectrum that it does absorb photocatalyzes degradation of the organic component. The researchers consider that it comprises an inert 50 percent of the volume of the composite cell with respect to light absorption, and thus it cuts the theoretical upper limit to cell efficiency in half. This is not obvious from the information supplied. For one thing, the characteristic lateral dimension of the mesoporous absorber, 10 nm, is much smaller than the wavelength of the light, on the order of 1,000 nm. Some average mean field theoretical model describing the absorption process might be more appropriate than the model the researchers have in mind, a heterogenous method of mixtures. This conclusion deserves another look, perhaps with further theoretical input in the form of a realistic calculation of the dielectric constant of the composite system. The second reason cited for dropping titania, namely its photocatalysis, may be amenable to ultraviolet blocking agents or making the organic material more resistant to degradation, which the researchers mention but discard due to the 50 percent-inert issue. If, however, the titania is not a 50 percent-inert component in the light-absorption process, then methods of eliminating degradation deserve investigation.

To avoid these issues, the researchers, in separate research, appear to be dropping the titania approach in favor of a “solution-processable, strongly light-absorbing, and stable inorganic, nanocomposite, semiconductor material based on elements from the well-researched I-III-VI semiconductor family. This includes copper-indium-gallium-diselenide-based absorber material, in the form of quantum dots, which can be coated from solution and which is amenable to high-volume manufacturing.” They state that initial test devices have already shown a power-conversion efficiency greater than 5 percent. One wonders if they are being too quick to drop a titania-based microstructure (titania being a relatively robust and simple material), in favor of a perhaps less robust quantum dot system comprising a doped ternary compound.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow-on funding within the PIER Program.

Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research would be increased affordability of electricity in California. A flexible, plastic, photovoltaic cell produced by roll-to-roll processing has low-cost potential. The researchers estimate that this technology will allow production of solar electricity cells that reduce the cost per areas from more than \$300 per square meter (the price of mainstream, state-of-the-art, polycrystalline silicon cells) to less than \$30 per square meter. In conjunction with target module efficiencies of 8 to 10 percent, this would enable solar energy to have grid-competitive (under 10 cents per kWh) electricity pricing. This compares favorably with carbon-based fuel-powered utility costs of the recent past as low as \$0.052 per kWh (natural-gas-fired combined cycle August 2003). It is significant that rates for carbon-based fuels likely will be higher in the future, favoring renewable-powered generation, which is much more immune to increases in the cost of fuel.

Additionally, the research offers a secondary benefit to the ratepayer in reduced environmental impacts of the California electricity supply or transmission or distribution system. Because of its capability to export power to the grid at times which nearly coincide with peak air-conditioner demand for electricity, this solar-powered distributed generation would lead to a reduction of the imbalance between peak electric demand and supply in the state. Accordingly it would reduce the need for new, large-scale, utility-generating plants and transmission lines.

2.15. Novel Nanocomposite Carbon Molecular Sieve Membranes

Awardee: University of Southern California
Principal Investigator: Muhammad Sahimi

Introduction

Separating the components of gas mixtures is important for many electric power generation processes and controls. The primary application for separation technology is renewable fuels, such as landfill gas and biogas. These potential fuels could be an important source of energy for California. They typically consist of roughly equal amounts of carbon dioxide (CO_2) and methane. The large fraction of CO_2 makes them difficult and mostly uneconomic to burn in power generation. An effective means is needed to separate and remove the substantial amount of CO_2 in these fuels. Another application for gas separation involves separating hydrogen (H_2) from methane (CH_4) for use in fuel cells. Other important applications of more effective gas separation include the upgrade of natural gas, and gasses from biomass and coal gasification. Separating components of gaseous mixtures is currently costly, energy inefficient and ineffective.

Standard technology for separating hydrogen from CO_2 and methane from CO_2 consists of either adsorption/desorption, or absorption methods. Both approaches are very capital-intensive. Membrane-based separations, as a result, are beginning to make inroads. Typically these membranes are made with polymeric materials. The polymeric membranes are generally cheap and easily processed into a variety of shapes (eg: sheets, tubes, hollow fibers). However, these very characteristics limit their separation effectiveness, especially towards gases like H_2 and CO_2 . Polymeric membranes cannot be produced with consistent, molecular size pore to act as sieve passages. To improve on the separation properties of polymeric membranes, several researchers have prepared membranes made with inorganic molecular sieve materials, like silica and zeolites. These materials, however, are expensive, brittle, and typically difficult to process. Mixed-matrix membranes, prepared through incorporating molecular sieves into a polymeric matrix, have been proposed, maintaining the high gas selectivity benefits of molecular sieve media without the costly processing of single component molecular sieve membranes. A number of preliminary studies have already appeared reporting some promising results in terms of enhanced separations.

Improved efficiency and effectiveness of gas separations using easily manufactured and durable membranes would allow more cost-competitive utilization of renewable fuels, such as landfill gas, biogas and synthetic gasses from biomass, and coal gasification. Another application for gas separation involves treating fuel gas for use in fuel cells. This could reduce the cost of electricity in that application. Improved efficiency of gas separation should improve costs associated with flue gas capture of carbon dioxide for sequestration, reducing the cost of global warming mitigation.

In this project, the researcher investigated new approaches using carbon molecular sieves (CMS) to overcome the challenges encountered during the preparation of composite mixed-

matrix membranes. The researcher proposed a novel electro-spray pyrolysis approach for fabricating a “hybrid” membrane with embedded CMS particles. The researcher hypothesized that the “hybrid” membrane would provide the physical flexibility of polymeric membrane substrates with the higher separation properties of molecular sieves. The researcher hypothesized that the carbon based molecular sieve material should be more chemically compatible with the carbon based polymeric substrate. Earlier attempts using inorganic molecular sieves were not effective.

Objectives

The goal of this project was to determine the feasibility of utilizing composite carbon molecular sieve membranes in the separation of hydrogen (H_2) and carbon dioxide (CO_2) from gas mixtures of relevance to power generation. The researcher established the following project objectives:

1. Fabricate subscale prototype composite mixed matrix membranes for H_2 and CO_2 separation.
2. Demonstrate that the prototype membranes are capable of separating H_2 and CO_2 in select binary, ternary, and quaternary mixtures, also containing carbon monoxide (CO) as one of the components.
3. Demonstrate the ability to produce composite mixed matrix membranes with the following characteristics:
 - CMS nanoparticles in the range of 10 nanometers (nm) to 100 nm with open porosity and the desired pore structure.
 - H_2 and CO_2 permeances in excess of 5.4×10^{-8} moles per square metre second pascal ($mol/m^2 s Pa$).
 - H_2/CH_4 separation factor in excess of 25.
 - CO_2/CH_4 separation factor in excess of 50.

Outcomes

1. The researcher fabricated several mixed-matrix polymer-base subscale prototype composite mixed matrix membranes (MM-PM) for H_2 and CO_2 separation with a carbon loading in the range of 15 to 35 weight percent using flat-sheet solution casting. He also fabricated supported hybrid mixed matrix carbon molecular sieve subscale prototype composite mixed matrix membranes (MM-CMSM) for H_2 and CO_2 separation by dip-coating techniques. The researcher created the carbon particles of approximately 500 nanometers (nm) in average size by wet-grinding size reduction techniques.
2. The researcher measured H_2 , CH_4 , and CO_2 permeation characteristics of MM-PM with carbon content in the range of 15 to 30 weight percent. The CO_2 and CH_4 permeability increased with increasing carbon content compared to the base-polymeric membrane. The CO_2/CH_4 and H_2/CH_4 selectivities remained either unchanged or reduced. The researcher suggested that this is due to the poor adhesion between the polymer and the carbon particles. Since the MM-PM did not provide better characteristics than the base polymeric membranes, they were not tested with mixed gasses. The researcher also prepared supported MM-CMSMs. The researcher tested ideal separation characteristics

with single gas measurements. The researcher also tested the membranes with binary (CO_2/CH_4 and H_2/CO_2), ternary ($\text{CO}_2/\text{H}_2/\text{CH}_4$), and quaternary ($\text{CO}_2/\text{H}_2/\text{CH}_4/\text{CO}$) mixtures.

3. The researcher successfully prepared composite mixed matrix membranes. These membranes had the following characteristics:
 - a. They contained CMS sub-micron size particles with an average size of near 500 nm made by wet-grinding techniques. The researchers also investigated the preparation of polymeric nano-particles made of polyetherimide (PEI), to be used, in the preparation of CMS nano-particles, using electro-spray pyrolysis. Stable, PEI nano-particles with an average particle size of near 200 nm were prepared, but the low productivity rate of the electro-spray technique did not allow for the use of these particles in membrane preparation.
 - b. A CO_2 permeance about 9.0×10^{-8} (mol/m².s.Pa) was achieved for the supported MM-CMSM (measured at 293 Kelvin and $\Delta P = 30$ pounds per square inch (psi)). The hydrogen permeance was reported at 9.7×10^{-8} (mol/m².s.Pa).
 - c. An H_2/CH_4 separation factor of 130 was obtained.
 - d. A CO_2/CH_4 separation factor of 120 was obtained with a CO_2 permeance about 9.0×10^{-8} (mol/m².s.Pa).

Conclusions

The feasibility of using mixed matrix membrane with nano-sized particles in a carbon molecular sieve was not established. The permeance of the particles the researcher produced and tested exceeded objectives for single gasses in binary mixes. The particle size of the CMS was well above the intended nano-particle size, approximately 500 nm on average. Production of PEI particles for use in membrane production was low. Fundamental properties and behavior of nano-particles are different from the properties and behavior of the same materials when they are of larger size. The researchers did not establish the performance behavior of nano-particles but did establish good performance with the larger particles.

Recommendations

Future research should focus on continued development of the carbon molecular sieve composite membrane with particle sizes as tested. Additional research may include developing methods for improved production yields for smaller particle size than demonstrated in this project. Research should also investigate multiple gas mixtures and develop separation factor performance maps (eg: performance at different CMS loading factors, different component gas ratios).

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for subsequent funding within the PIER Program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is reduced environmental impact of the California electric supply system. This includes the ability to use additional renewable resources, such as landfill and digester gas, in advanced generation technologies such as fuel cells or in gasification-based systems. This research also provides improved potential for capture and ultimate sequestration of carbon dioxide from carbon based fuel use.

Estimating the potential market and, consequently, actual benefits for this technology is speculative. However, 117 megawatts of landfill gas, and 106 megawatts of energy from animal manure could be developed in a more cost-effective manner using advanced gas separation. Further, the existing carbon based generation capacity in California (about 35 percent of total capacity) could potentially be retrofitted to capture carbon dioxide and reduce greenhouse gas emissions. It will likely take seven to ten years, or more, of development and commercialization before this technology begins to provide significant benefit to California.

2.16. Build and Test a 3 Kilowatt Prototype of a Co-Axial, Multi-Rotor Wind Turbine

Awardee: Selsam Innovations
Principal Investigator: Doug Selsam

Introduction

Harvesting California's wind generation potential depends on availability of cost-effective, reliable, environmentally compatible wind turbines. The trend toward ever-larger rotors to harness more power at a given location leads to several design challenges which may limit this approach's ability to optimize these three key drivers. Larger blades produce less power for the amount of material required: Blade weight varies as the cube of diameter, whereas power varies as the square of diameter. The slower rotation of large blades requires gearing to drive a generator (or a specially designed low-speed generator), and since torque increases with the cube of diameter, gearbox design, and maintenance are negatively impacted. For many stakeholders, the larger, slower turning rotors exacerbate visual environmental impacts.

A wind turbine design that would produce equivalent or better power as the single-rotor approach without introducing the burdens associated with larger rotor sizes described above

could reduce cost, improve reliability, and reduce visual impacts. This could translate into lower electricity costs to California ratepayers and result in a larger quantity of renewable energy from wind available to the state.

The researcher designed and tested a self-aiming turbine that used multiple rotors mounted on a common driveshaft, thereby eliminating the need for a gearbox, and drastically reducing rotor size compared to a single rotor unit of similar power output. An innovative turbine mounting mechanism that allows the shaft to tilt as much as 25 degrees from horizontal, exposed each set of blades to fresher wind and helped protect them from high wind events.

Objectives

The goal of this project was to determine the feasibility of a new type of horizontal axis wind turbine, in a 3 kilowatt (kW) prototype. A co-axial, multi-rotor horizontal-axis turbine utilized an elongated driveshaft with seven rotors mounted coaxially at regular intervals, rather than a single rotor. A new type of furling mechanism allowed the shaft to be blown into a horizontal orientation for protection in high winds. The researchers established the following project objectives:

1. Fabricate a 3-kW, co-axial, multi-rotor wind turbine (U.S. patent application number 09/997,499).
2. Demonstrate an output of 3 kW from the prototype wind turbine in 27 miles per hour (mph) wind.
3. Demonstrate full power generation at wind speeds of 27 mph to 45 mph.
4. Demonstrate power output that is at least 3 times higher at low and medium wind speeds (up to the rated wind speed of 27 mph) than a single-rotor turbine of the same diameter.
5. Demonstrate the capability of the design to protect the turbine against overspeed in winds up to 50 mph or if this speed is not reached, the highest wind speed measured during the testing period.
6. Demonstrate wind turbine durability by completing the 6-month testing period with at least 90 percent uptime.
7. Based on the data generated in this project, show that the projected life cycle cost of power of \$.04 per kilowatt hour (kWh) for the proposed 3 kW design continues to be supported.

Outcomes

1. The turbine was built with 7 rotors, each 7 feet in diameter, and mounted on a single, 70-foot-long tubular carbon fiber driveshaft.
2. Output of the turbine was 4.5 kW (corrected to sea level) in the targeted 27 mph wind, well above the design target of 3 kW. With a conservative setting to begin furling at 16 mph, the turbine still met the targeted output of 3 kW in a 27 mph wind.
3. Turbine output was 5.5 kW at a 30 mph wind speed, increasing to 6 kW or more at wind speeds between 33 mph and 45 mph.

4. Output was 5 to 6 times the power of a single-rotor turbine of the same diameter at all tested wind speeds.
5. The turbine survived wind speeds up to 45 mph, the maximum speed encountered during the course of the study, with no damage, while maintaining full power output (between 5 and 6 kW at these speeds) and smooth operation. The tilting mounting mechanism (U.S. Patent 6692230) functioned as designed, allowing the shaft to rotate toward the horizontal from the default 25 degree upward tilt as wind speeds increased, thereby mitigating the amount of fresh wind striking all but the front rotor for overspeed protection.
6. The turbine operated during most times of sufficient wind during six months of testing over an eight month period. Overall the unit was fully deployed in operational mode for 90 percent of the six-month target duration. Other than adjustments to fine tune performance, there was no required maintenance or repair of the turbine.
7. Total cost for the prototype was not presented in the final report, nor was there information about the cost of a single-rotor unit of equivalent total capacity. The principal investigator calculates that elimination of the gearbox in single-rotor machines would result in a 17 percent turbine cost reduction, leading to a 10 percent life-cycle power cost savings, but does not show a supporting calculation of the life-cycle cost of power from the prototype design utilizing actual costs from the research.

Conclusions

1. The objective of fabricating a 3 kW unit was met.
2. Turbine output exceeded the objective by 50 percent and met the objective even with a very conservative furling adjustment that began to reduce output at 16 mph wind speeds.
3. The turbine operated smoothly throughout a wide range of wind speeds, up to the highest encountered speed of 45 mph, meeting the objective for operation at high wind speeds.
4. Output of the 7-blade unit was well above the targeted 3 times the output of a single-rotor turbine with the same diameter as the blades used in the tested unit, ranging between 5 and 6 times that of a single-rotor unit.
5. The patented tilting mechanism protected the turbine through wind speeds up to 45 mph (the highest encountered), and allowed smooth operation at higher wind speeds through its furling design, meeting the targeted objective.
6. The turbine met the objective for 90 percent operation during the six-month test period. There was no equipment failure or required corrective maintenance.
7. Without “all in” cost data for the tested unit and for a single-rotor unit of equivalent output, it is not possible to verify whether the “all in” costs of a production multi-rotor turbine would likely be sufficient to meet the targeted \$0.4 per kWh life cycle target, or be less than a conventional single-rotor turbine of equivalent capacity. However, the research did provide useful cost insights: The principal investigator states that the savings in rotor costs resulting from less required material than for a single rotor of an

equivalent capacity were roughly offset by the cost of the longer shaft required to support the multiple rotors. The most immediate savings opportunity is elimination of the gearbox (estimated at 17 percent of the cost of current systems), along with its associated maintenance and repair. Other cost savings should be possible through avoiding the need to transport very large single rotors to sites, especially those in remote locations.

This was a successful physical demonstration of the concept, design, and operation of a co-axial multi-rotor wind turbine. Output of the prototype exceeded the target; the innovative mount provided clearer wind for the downwind rotors during normal operation and protected them from overspeeding in high winds; and the unit operated successfully for six months under a range of conditions. Whether the life cycle cost of a production unit would compete effectively with existing single-rotor designs will depend on further testing and refinement of the various cost elements in this approach and a comparison with comparable single-rotor machines.

Recommendations

1. Provide a follow-on report with details of the full cost of the equipment utilized, and a comparison to the cost of a single-rotor unit with equivalent output.
2. Conduct similar testing at a second location, with different wind regimes and topography (perhaps at the National Renewable Energy Laboratory in Colorado).
3. Extend the test duration beyond six months to further evaluate operation and maintenance requirements of the design.
4. Conduct noise studies and compare results to a single-rotor design with equivalent output.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow on funding within the PIER Program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is its potential to increase the amount of wind-generated electricity available to California, thereby reducing environmental impacts of

the California electricity supply. This potential can occur in several ways, assuming the positive indications from this research lead to successful development of commercial multi-rotor machines. For example, avoiding the need for ever-larger rotors to develop large amounts of power at a location could reduce the installation costs and overcome the potentially prohibitive access to some sites inherent in large rotor machines, fostering additional wind development. Additional sites could also become available due to the design's mitigating the visual impacts of large, slow-turning rotors.

2.17. Hydrogen Blower Design for Fuel Cell Recirculation Applications

Awardee: H₂Systems, Inc.
Principal Investigator: J. Patrick Sterchi, Ph.D.

Introduction

Fuel cells promise to generate highly efficient, environmentally benign power for residential and small commercial markets. Cost reduction and improvements in cell-stack life are particularly critical for fuel cells to achieve acceptance in the market. The successful deployment of hydrogen fuel cells for power generation would reduce pollutants and greenhouse gases, as well as help alleviate constraints on electricity capacity and the transmission and distribution system in California.

A hydrogen recirculation system, if successfully developed for proton exchange membrane (PEM) fuel cells, would improve fuel cell performance, increase durability, and reduce the amount of platinum catalyst required to promote the anode electrode reaction. The project researcher estimated that the amortized value of the catalyst reduction alone could save \$0.003 per kilowatt hour (kWh) over the life of a fuel cell. This enhancement could help fuel cells move toward economic viability. At that point the environmental, efficiency, and security benefits of fuel cells could produce significant market inroads.

Over the next 20 years, a successful fuel-cell initiative could result in 2 gigawatts (GW) or more of PEM fuel cells in California. At a benefit of \$0.003 per kWh, the annual savings of the recirculation feature after twenty years of market penetration, excluding its impact on accelerating market adoption, is estimated at \$30 million.

The researcher proposed a hydrogen recirculation blower that moves excess hydrogen at the exit of the fuel-cell stack (commonly known as anode tail gas) back to the inlet of the fuel-cell stack. The blower is a centrifugal design with a regenerative or "vortex" impeller configuration. The selected design has several attractive qualities: small size and weight; little-to-no maintenance; oil-free, adjustable electronic control; relatively low power consumption; and a wide temperature operating range. The unique blower design provides a method of pumping low-density fluids such as hydrogen, while maintaining a hermetically sealed containment of the process fluid. The availability of this technology could enable tail-gas recirculation with a

cost-effective, “off-the-shelf” blower. The design is applicable to PEM fuel cells in the range of 1 to 10 kW.

Objectives

The goal of this project was to determine the feasibility of using a centrifugal blower for the recirculation of anode tail-gas in a 1 to 10 kW, hydrogen-fueled PEM fuel cell. The researchers established the following project objectives:

1. Construct a working prototype blower, capable of supporting the recirculation requirements of a 1 to 10 kW PEM fuel cell.
2. Demonstrate 500 hours of operation in a humidified hydrogen environment without failure.
3. Verify that the blower is capable of achieving the following performance capabilities:
 - Can be mounted in any orientation.
 - Can function at motor temperatures of -30 degrees to 125 degrees Celsius.
 - Can maintain a maximum rotational speed of 35,000 revolutions per minute (rpm).
 - Can achieve projected flow rates and pressure differentials
4. Project a manufacturing cost of \$250 to \$300.

Outcomes

5. A 7 centimeter-diameter blower capable of supporting 1 to 10 kW fuel cells was designed. The blower components were selected (motor) and fabricated (impeller, housing, seals, tubes, and fasteners) according to the design specifications. The blower was assembled and successfully passed initial functional testing.
6. Under simulated fuel-cell operating conditions, pumping saturated hydrogen gas at 65° Celsius and 1.5 atmospheric pressure (bar) absolute, the blower performed without incident during a 500 hour test. Minor degradation was noted on the outside of the impeller fins and on a brass lock nut that was specified to be stainless steel.
7. Performance testing with three different blower orientations showed no difference in results. The researcher found neither start-up problems at -30 degrees Celsius nor any performance degradation at temperatures above 100 degrees Celsius. The unit demonstrated an ability to maintain a maximum 35,000 rpm speed for 8 hours. The flow-vs.-pressure drop was about 20 percent off the predicted performance. The energy consumption of the unit was measured at 59 watts at maximum output, about 50 percent higher than projected.
8. The cost to produce the first blower unit was \$941, with the motor accounting for \$200. In high volumes (1,000 to 10,000 units), and with injection molding tooling, the researcher projected production costs at 20 percent of the prototype unit (close to \$290).

Conclusions

1. The blower design proved to be functional, with parts either readily available or easily manufactured.
2. The blower prototype performed as designed under simulated fuel-cell conditions over a 500-hour period. Fixes to isolated component materials durability problems were identified. Future blower impellers will incorporate the polyetherimide Ultem TM, an amorphous, thermoplastic polyetherimide that has demonstrated better compatibility with humidified hydrogen.
3. The following performance results were achieved:
 - The blower can be mounted in any orientation.
 - The unit can function at a wide range of motor temperatures demonstrating the ability to start up below freezing temperatures and to operate at high internal case temperatures.
 - The prototype unit can maintain maximum speed and flow rate for sustained periods of time.
 - The relationship of flow rate to pressure drop did not meet the original specifications and will require a design change for the impeller.
 - The power requirements were significantly higher than projected, warranting impeller-blade optimization to improve pumping efficiency.
4. The design lends itself to low manufacturing costs in modest production volumes. This project demonstrated that the proposed blower design is feasible and capable of meeting the functional and durability requirements for the recirculation of hydrogen in a 1 to 10 kW PEM fuel cell. Component inspection after the durability test revealed little wear on the unit, indicating that much longer run times are feasible for this design. However, there were signs of wear on internal components made of Delrin TM. These components should be fabricated from an upgraded material in the design of the next generation.

Recommendations

The proposed recirculation compressor appears to address an important component gap among PEM fuel-cell developers. Further efforts should correlate performance with the newly refined computer model, should prove the material changes, and should verify durability of 5,000 hours or more. Once these tests have been successfully completed, the researcher should establish partnerships with fuel-cell developers. The developers should integrate and test the compressor technology in prototype fuel-cell systems.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow-on funding within the PIER Program.

Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefits to the ratepayer from this research are reduced environmental impacts of the California electricity supply or transmission or distribution system. A commercially viable, hydrogen-fueled, fuel-cell power plant exhibits the near absence of pollutant emissions and greenhouse gases. This, along with its relatively high fuel efficiency, would make PEM fuel cells a preferred means of distributed-power generation. The hydrogen blower improves overall fuel-cell economics by reducing the operating cost. This should hasten the commercialization of PEM fuel cells.

2.18. Emission Monitoring of Nitric Oxide With a Mid-Infrared Solid State Laser

Awardee: The Regents of the University of California, San Diego
Principal Investigator: V. Ramanathan

Introduction

Advanced combustion technology for electric power generation has reduced the emission levels of nitric oxide (NO) in exhaust gasses. Nitric oxide levels in the exhaust stack can approach one part per million for combustion engines and be considerably lower for fuel cells. Traditional emission monitoring using chemiluminescence is not sufficiently precise at these lower concentration levels. Further, traditional analysis methods require sample extraction and do not easily allow for continuous monitoring.

Solid state laser technology provides the opportunity for the next major advance in trace species detection. The quantum cascade laser provides tunable mid-infrared light to access nitric oxide absorption features near five microns and perform concentration measurements averaged over the length of the laser beam path. At atmospheric pressure and room temperature nitric oxide detection at 0.050 parts per million meters (ppm-m) has been demonstrated with a minimum detection limit of 0.003 ppm-m. In combustion exhaust applications care must be taken in the selection of the laser wavelength to access nitric oxide absorption transitions that do not have interference from overlapping water vapor transitions. The nitric oxide detection limit in combustion exhaust gas with this laser absorption technique is dependent on the gas

temperature that affects available nitric oxide transitions to be accessed and interference from water vapor.

The primary goal of this project was to determine the feasibility of improving the minimum measurement limits for NO at combustion exhaust conditions using mid-infrared laser spectroscopy. To perform these measurements a one-meter long combustion exhaust simulator was constructed. The simulator is fed with methane/argon/oxygen combustion exhaust from a premixed burner (to assure no nitric oxide formation) mixed with additional argon to obtain the required temperature. The laser beam travels through the chamber entering and exiting two calcium fluoride (CaF_2) windows.

Objectives

The goal of this research project was to prove the feasibility of mid-infrared laser absorption spectroscopy for measuring NO at typical combustion exhaust conditions of advanced gas turbine generators. To accomplish this goal, the researchers established the following objectives:

1. Develop a one-meter long combustion exhaust gas simulator with optical access, verify that the exhaust simulator is capable of maintaining a temperature of 500 Kelvin, which is equivalent to gas turbine exhaust conditions and verify that the exhaust simulator can produce NO concentrations in the range of 0.1 to 1 ppm-m with an accuracy of plus/minus 0.05 ppm-m.
2. Model the expected infrared absorption spectra for nitric oxide and verify (a) the elimination of interference from water vapor and other combustion species at the combustion exhaust composition and temperature and (b) the theoretical accuracy of the nitric oxide concentration measurement based on the absorbance.
3. Demonstrate the a nitric oxide sensor based on a mid-infrared quantum cascade laser is capable of measuring NO concentrations in the range of 0.1 to 1 ppm-m with an accuracy of 0.05 ppm-m.
4. Develop a cost estimate for the commercial use of this mid- infrared laser measurement of NO.

Outcomes

1. The researchers designed, built and tested a combustion exhaust gas simulator that met the requirements of simulating the exhaust stream from a combined cycle, gas turbine power plant with an exhaust temperature of 550 Kelvin.

A methane/oxygen/argon burner and complementary electrical heating of the 1 meter absorption cell provides for temperature control within 0.1 Kelvin. Control of the NO concentrations through doping of NO/Argon mixtures provided control over two orders of magnitude from one to 100 ppm-m. In the range of one to 10 ppm-m, NO control precision was within 0.5 ppm-m.

2. The researchers simulated the NO and water (H_2O) absorption spectra in the wavelength range of the quantum cascade laser at 5.3 microns. The absorption line in the NO spectra at 5.263 microns was chosen for the NO absorption measurements because of no interference from H_2O .

The researchers calculated the theoretical detection limit for nitric oxide concentration in the combustion exhaust gas simulator using the Hitran 2004 data base over the temperature range from 295 to 2,100 Kelvin. At a temperature of 550 Kelvin, the minimum theoretical detection limit for nitric oxide is 0.669 ppm-m for an absorbance of one percent.

3. Laser absorption measurements were made in the range from one to 20 ppm-m. Agreement between measured and seeded NO concentration was within 0.75 ppm-m between 20 and approximately 10 ppm-m. Below 10 ppm-m baseline drift in the direct absorption measurement introduced significant systematic error. The random noise error in the spectra used to determine the absorbance was approximately one ppm-m. The theoretical detection limit of near 0.7 ppm-m for the laser measurement was not attained.
4. The researchers estimated the cost of a pulsed Quantum Cascade (QC) laser for the measurement of NO concentration from mid-infrared laser absorption, based on commercially available components. A laser system cost (\$40,000) is slightly higher than a conventional chemiluminescence analyzer (\$35,000) for a single measurement location.

Conclusions

1. A combustion exhaust gas simulator was designed, constructed and successfully tested to meet the design requirements for evaluating mid-infrared laser absorption, or any other advanced analytic process for the measurement of NO.
2. The modeling of NO absorption was successfully completed with the use of the Hitran 2004 database and associated Java Hawks operating program. The theoretical detection limit in the measurement of NO with direct absorption measurements with an absorbance of one percent is 0.669 ppm-m at a temperature of 550 Kelvin.
3. The minimum detection limit for NO observed in the combustion exhaust gas simulator was substantially above the theoretical limit of near 0.70 ppm-m at an absorbance of one percent. For NO concentration levels below 10 ppm-m, systematic errors due to baseline drift in the direct absorption measurement limited the accuracy of the measurement.
4. The laser system is more costly, \$40,000 versus \$35,000, than conventional chemiluminescence. The cost comparison of the two systems is based on a single measurement location and does not include maintenance costs. As multiple measurement locations are included in a system the cost for a quantum cascade laser system could be less than that of a chemiluminescence system, since it can be multiplexed more cheaply for multiple measurement locations.

The researchers did not demonstrate feasibility of the technology, as the minimum detection limits were well above established goals and theoretical limits.

Recommendations

Although NO absorption line shapes could be observed directly down to two ppm-m, the integrated absorbance was limited by random noise in the signal equivalent to approximately one ppm-m. Improvement in the theoretical and measured detection limits for the quantum cascade laser measurement of NO can be accomplished by using wavelength modulation

spectroscopy instead of direct, single wavelength absorption. Typically, direct absorption measurements can be made as low as one percent beam absorbance. In the case of NO this results in the minimum theoretical detection limit of 0.70 ppm-m. With wavelength modulation spectroscopy, where the laser wavelength is modulated at a frequency "f" as it is scanned over the absorption feature and the detector signal observed with a lock-in-amplifier at a frequency 2f, the minimum theoretical detectable absorbance that can be reduced. The lock-in-detection might remove the baseline drift problem associated with the direct absorption measurement performed in this experiment and also suppress the random noise that was observed.

Further, the researchers should investigate modifying the split beam set-up, to include an absorption cell identical to the test beam in the reference beam, at the same temperature and contained gasses but without NO. In the project, a reference detection cell was used in a split beam set up, but no reference beam cell path.

Finally, the researchers may wish to consider investigating lengthening the beam path by use of partial mirrors on the cell windows, which should increase sensitivity for absorption, by increasing the effective beam path length and sensitivity.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for subsequent funding within the PIER Program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply system. This project has provided an objective evaluation of a new measurement technique for (continuous) emission monitoring. This laser technology is relatively new, but once developed, it could improve the control and management of combustion sources such as combustion turbines. The mid-infrared laser offers at least two orders of magnitude improved theoretical sensitivity. The results of this project demonstrated both the potential and limitations of the use of mid- infrared laser as a NO emission monitoring measurement technology. This research documents the detection sensitivity and recommends improvements in this measurement technique that could be implemented in future demonstration projects. Improved measuring of emissions does not directly reduce

environmental impacts but improves the management and control of sources, which does lead to reduced impacts from upset conditions and suboptimal operations. It is premature to make estimates of market penetration or specific environmental improvements until the technology's specific cost and performance are more specifically established.

2.19. Carbon-Catalyzed Natural Gas Processing

Awardee: Sunnyside Technologies, Inc.
Principal Investigator: Steve Chu

Introduction

California's environment would improve if hydrogen (H_2) could be produced from natural gas such as methane (CH_4) without producing carbon monoxide (CO) or carbon dioxide (CO_2) as a byproduct. Hydrogen thus converted from natural gas is the ideal fuel for fuel cells to be used in future stationary electrical generation with no pollutants emitted.

Compared with steam reforming, the proposed carbon catalyzed natural gas process would produce H_2 of higher purity without the necessity of expensive carbon sequestering. The researchers estimated the new process would produce hydrogen for less than \$2.00 per kilogram (kg) compared with \$2.10 per kg for steam reforming. There would be further savings in transportation and storage by utilizing decentralized, on-site conversion plants rather than centralized plants used for steam reforming. The cost for delivery using centralized plants would be an additional \$1.50 to \$3.00 per kg of hydrogen.

The carbon catalyzed technique utilizes nanostructured carbon material as a catalyst for natural gas processing. The process yields 99 percent pure hydrogen with undetectable carbon monoxide and a conversion efficiency of up to 88 percent.

Objectives

The goal of this project was to determine the feasibility of producing CO-free hydrogen and nanostructured carbon through the chemical vapor reaction of natural gas catalyzed by the nanostructured carbon itself. The products of this reaction, hydrogen and carbon, can be used as fuels for fuel cells, and the yield conversion factor will be higher than conventional thermal cracking process at high temperature. The researchers established the following project objectives:

1. Demonstrate that the proposed modifications to a chemical reactor are capable of producing 600 liters per hour of hydrogen.
2. Demonstrate that the hydrogen produced contains undetectable CO.
3. Demonstrate the ability to convert 60 percent of the CH_4 feedstock to H_2 in a single pass, which is equivalent to four times the yield of the conventional thermal cracking process.

4. Demonstrate that the projected hydrogen production can be achieved at a temperature between 1,000 and 1,300 degrees Celsius.
5. Demonstrate that the CH₄ conversion to hydrogen can occur in less than 1.0 second residence time in the chemical reactor.
6. Demonstrate that the H₂ and carbon can be successfully separated from the stream.
7. Confirm that the nanostructured carbon produced in conjunction with the H₂ production has the desired electrochemical properties needed for use in carbon fuel cells.
8. Determine the optimal parameters (temperature, residence time, CH₄ concentration, flow rate, and bed surface area) for maximum H₂ yield from CH₄.

Outcomes

1. The spouted bed reactor filled with carbon particles operated at a temperature of 1,350 degrees Celsius utilizing 12 to 18 liters per minute of CH₄. The resulting CH₄ conversion varied from 33 percent to over 88 percent depending on experimental conditions. The researchers did not measure the resulting H₂ directly. They based the conversion efficiency on the amount of carbon produced. The researcher claimed a hydrogen output of over 1,000 liters per hour.
2. The level of carbon monoxide was undetectable in the spouted bed tests because no oxygen was introduced at any point.
3. The conversion of CH₄ to carbon and hydrogen was achieved at efficiencies of up to 88.5 percent, greater than the 60 percent target.
4. The actual hydrogen production described above was achieved at 1,350 degrees Celsius, higher than the targeted 1,000 to 1,300 degrees Celsius.
5. The researchers reported reaction time to be less than one second contacting time to reach the targeted conversion and yield. However, there were no specific data that showed how this contact time was calculated.
6. The researchers showed carbon and hydrogen successfully separated by the measurement of carbon produced during the tests.
7. The researchers studied the produced carbon in the bed using X-ray diffraction and transmission electron microscopy (TEM). They found the structure of the carbon had a nanostructure that could be favorable for use as fuel in direct carbon fuel cells. They stated the resulting nanostructure carbon might be used for other valuable applications.
8. The researchers determined the optimal parameters for high yield conversion were as follows:
 - a) Temperature greater than 1,350 degrees Celsius.
 - b) Hydrogen conversion approximately 75 percent or better.
 - c) Flow rate/bed weight equal to 12 cubic centimeters per 5 grams per minute.
 - d) Residence time: assumed to be one second but not calculated.
 - e) Bed surface area: not reported.

Conclusions

1. The spouted bed reactor converted CH₄ to H₂ at a rate of over 100 liters per hour of hydrogen.
2. No carbon monoxide was produced as a byproduct of this conversion.
3. The best efficiency achieved of CH₄ to H₂ conversion was approximately 88 percent.
4. The temperature required for the best efficiency was 1,350 degrees Celsius.
5. Researchers reported the reaction time was less than one second.
6. The carbon was successfully separated from the hydrogen produced by this reaction.
7. The nanostructured carbon produced was suitable for carbon fuel cells.
8. The optimal parameters for 88 percent conversion of CH₄ to H₂ included a temperature of approximately 1,350 degrees Celsius and a flow rate to bed weight ratio equal to 12 cubic centimeters per grams per minute.

In summary, the researchers achieved all of the goals of this study in producing hydrogen at high conversion rates from CH₄ in a carbon bed reactor. The researchers reported that 720 liters per hour of CH₄ could be converted to 1,440 liters per hour of H₂ at 1,350 degrees Celsius. The resulting nanostructured carbon could be suitable for carbon fuel cells or industrial uses of fine carbon.

Recommendations

Future work should focus on developing commercial size units based on using natural gas rather than pure methane. Using natural gas may result in the production of unwanted gas components. The researchers should also develop the necessary materials handling and hydrogen gas cleanup. Finally, the researchers should carefully calculate the energy balance to ensure that this process is energy efficient.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for subsequent funding within the PIER Program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research would be reduced environmental impact of the California electricity supply. The production of H₂ from CH₄ could be used as a fuel for fuel cells. The gaseous emissions including greenhouse gases would be significantly reduced compared with conventional natural gas power plants. The researchers predicted a direct energy savings for production of hydrogen from natural gas of 20 trillion British thermal units per year using the new process. The environmental benefits for California are highly dependent on the speed of market acceptance of PEM fuel cells. The deployment of fuel cells into individual residential applications may be decades in the future. More likely, newly built or renovated communities may employ fuel cells in shared community energy systems. Because of the depressed real estate market in 2009, it is not possible to predict when new communities will be built in California. Commercial application of fuel cells depends on a robust commercial sector of the economy. Again, in 2009 the commercial sector is quite weak.

2.20. Development of Universal Software for Dissolved Oxygen Control in the Activated Sludge Process

Awardee: Ekster and Associates, Inc.
Principal Investigator: Alex Ekster

Introduction

Sewage treatment plants in California presently use 3,000 megawatt hours (MWh) of electricity per day. The generation of this amount of energy via combustion-based generators produces significant amounts of air pollution. The state's environment would improve if sewage treatment plants could be made more energy-efficient. Most sewerage plants use activated sludge processing, which requires the addition of significant amounts of oxygen to the sludge. Because of past control limitations the plants usually error by introducing more oxygen than is necessary. By having more precise control of the operating parameters of the sewage treatment process, the wastewater would be more reliably treated to safe standards, while at the same time using less oxygen and energy to perform the required aeration.

The goal of this project was to develop software to precisely control the level of dissolved oxygen (DO) in the sludge while minimizing the energy used in the sewerage treatment plants. The researcher proposed to develop software utilizing data from sensors to accurately control the aeration motors. The researcher had an objective of saving 10 percent of the plant energy. If the project was successful and the software were applied in 90 percent of the sewerage plants, approximately 270 MWh would be saved daily. At \$0.10 per kilowatt hour (kWh) the value of the energy savings is approximately \$27,000 per day, or close to \$10,000,000 on an annual basis.

The investigators developed and tested full-scale, universal, and low-cost DO control software utilizing proprietary automatic fault detection and proprietary control algorithms. The DO control algorithm model utilizes feed-forward and feed -back control applicable to all DO sensors technologies.

Objectives

The goal of this project was to determine the feasibility of using a feed-back and feed-forward control algorithm to regulate dissolved oxygen levels in wastewater and thus save energy by optimally controlling aeration motor. The researchers established the following project objectives:

1. Investigate available DO sensor technology and develop a sensor fault detection algorithm applicable to three types of DO measuring technology: membrane, Zuligg (Zuligg, Inc.), and fluorescent/luminescent.
2. Develop a DO control algorithm that utilizes model-based feed-forward and feed-back control.
3. Develop airflow valves and blower control algorithms that will provide robust supply of airflow to each aeration zone at minimum energy cost.
4. Develop computer software utilizing the above DO control algorithm.
5. Test the software at a full-scale wastewater facility. Demonstrate that under real-world conditions the following sub-objectives were achieved:
 - a) 100 percent sensor fault detection during both normal operation and stress testing.
 - b) Standard deviation of DO does not exceed 0.25 milligrams per liter (mg/l) during normal operation and 0.5 mg/l during stress testing over measurement noise level.
 - c) Demonstrate a minimum 5 percent reduction in energy consumption used in the activated sludge process (ASP).

Outcomes

1. The researcher developed a fault detection algorithm based on pattern recognition. The software detected simulated sensor faults associated with malfunctions of dissolved oxygen meters based on the following technologies: membrane, galvanic cells, and new fluorescent technology.
2. The feedback control algorithm selected utilized the proportional-integral-derivative (PID) control law to control DO To improve the traditional PID algorithm for calculation of airflow, the researcher developed a new approach employing feed-forward and modified feed-back algorithms. The feed forward approach uses Case Base Reasoning (CBR) methodology that reused conditions from the past that are similar to current conditions to generate a feed-forward signal. In addition, the researcher used manufacturer's performance data to develop a gain-scheduling algorithm for a feed-back control algorithm.
3. The control strategy for blower and individual valve airflow controllers was developed using Simulink/Matlab modeling software. Using manufacturers' data for the blower, valves and air diffuser at the Oxnard Wastewater Treatment Plant, the researcher modeled the processes used at that plant.
4. The researcher developed software that utilized the algorithms described above.
5. The researcher installed the developed software on a personal computer networked with the plant control system. An operator-interface was developed. System tests were

conducted to test the sensor fault detection algorithm. The system developed in this project:

- a) Detected 100 percent of all faults using fault detection algorithms. It issued no nuisance alarm.
 - b) Provided a standard deviation of DO less than 0.1 mg/l above noise level under normal operating conditions and 0.3 mg/l above noise level under stress conditions
 - c) Reduced average energy consumption by 30 kWh representing a 15 percent savings.
6. Regular PID algorithms can be used for control of individual control valves. Tuning of these control valves can be done using traditional methodology. Utilization of PID algorithms for blower control can cause system oscillation, especially if blower pressure is used as a control parameter. Replacing the PID algorithm with a combination of Case Base Reasoning and fuzzy logic solved the problem.

Conclusions

The researcher proved feasibility in this project.

1. This project resulted in a reliable fault detection algorithm for each control element. The researcher proved performance at a full-scale facility.
2. The researcher developed a reliable and accurate DO control system utilizing feed-back and feed-forward strategies.
3. In a full-scale facility test the developed software reliably maintained DO at the set point. Neither valve nor blower vane showed any symptoms of oscillation.
4. The software was developed.
5. Energy savings at a full-scale facility exceeded 15 percent. Other conditions were met.
6. Traditional pressure-based control of the blower is inherently unstable.

Recommendations

The program administrator recommends:

- Continuing to work with the city of Oxnard wastewater treatment staff to investigate long-term performance of the project software (named DOmaster),
- Developing variety of communication drivers (software) for various existing control systems.
- Developing an optional stand-alone operator interface.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow on funding within the PIER Program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is from reduced environmental impacts due to better wastewater treatment at lower cost and lower energy consumption. The average benefit to a single 9 million gallons per day (MGD) plant located in California would be approximately \$40,000 in reduced electrical costs while maintaining the same or better level of wastewater treatment. The researcher intends to license the software with a \$30,000 first cost and a \$10,000 annual software maintenance cost. If the initial cost is amortized over 5 years, the annual rate of return on the investment is over 60 percent. For the whole state of California, the estimated electrical savings would be almost 100,000 MWh worth approximately \$10,000,000 annually.

2.21. Radio Frequency Electrostatic System Feasibility Demonstration

Awardee: EtaTech, Inc
Principal Investigator: Donald Taylor

Introduction

Distributed generation is one area of policy preference of the California Energy Commission. Advanced reciprocating engines are a major component of that policy. In recent years, industry and government have been working together to develop the next generation of high efficiency, low-emissions, natural gas fueled, industrial, reciprocating engines for power generation. The Department of Energy (DOE) and the Energy Commission have established goals of 50 percent efficiency and 0.1 grams per brake horsepower-hour (g/bhp-hr) by 2010. According to the major engine manufacturers, these goals cannot be met with current ignition system technology. Current ignition systems cannot consistently ignite very lean mixtures and are subject to electrode degradation. Further, the very high temperature inherent in current ignition systems lead to high nitrogen oxide (NOx) formation. The DOE and the Energy Commission have jointly developed a specification for the next generation ignition system, which will support meeting the engine cost, efficiency and emissions goals, necessary for advanced engines to expand the distributed generation market.

The development of an alternative ignition system that lowers the lean limit of combustion and avoids very high temperatures will help achieve the goals of high efficiency and low NOx emissions. These improvements in performance will enable advanced reciprocating engines to expand the distributed generation market. Overall, California will realize improved efficiency and reduced environmental impacts of the California electricity supply system.

In this project the researcher proposed a radio frequency electrostatic ignition system (RFEIS) EtaTech, Inc., proposed this system to meet the requirements of engine manufacturers. This system was evaluated in a combustion test chamber and has shown a significant improvement in combustion and ignitability for lean air-fuel mixtures over conventional ignition systems. It generates a high-voltage, low-current, radio-frequency electrostatic field inside the combustion chamber to efficiently ionize the air and fuel mixture and initiate multiple flame fronts. The system is capable of introducing much higher ionization energy to the combustion chamber than conventional ignition systems because the ionization uses a high voltage electric field, not high temperature. Conventional ignition systems generate temperatures of up to 30,000 degrees Fahrenheit in the spark plug gap. This temperature is created in the plug gap by a high current, low-voltage plasma arc. The reliance of the conventional ignition system on temperature to initiate combustion limits the maximum delivered energy because the high temperatures erode the electrodes. Spark plug lifetimes in engines with conventional ignition systems are often less than 1,000 hours. Since the RFEIS does not generate these high temperatures, electrode erosion is not a problem, and plug life should be greatly extended.

Objectives

The goal of this project was to demonstrate the feasibility of a radio-frequency electrostatic ignition system (RFEIS) for use on internal combustion engines to extend the lean limit of stable ignition. This researcher established the following seven objectives:

1. Design and machine a piston.
2. Design and optimize RFEIS electrostatic discharge and combustion characteristics using finite element modeling and combustion bomb testing.
3. Demonstrate at least 12 hours of durability of the RFEIS in a hot firing test engine.
4. Demonstrate between 0.1 to 0.5 grams/brake horsepower-hour (g/BHP-hr) NOx emissions with RFEIS in a single cylinder engine.
5. Demonstrate stable engine operation at 90 percent of the lean limit (40 to 1 air-fuel ratio).
6. Test a standard ignition system in a single cylinder engine and compare with RFEIS.
7. Verify that the data generated from this research support the ignition system's projected capital cost of \$8 per kilowatt-electric (kWe) and life cycle cost of \$.25 per megawatt-electric-hour (MWe-hr).

Outcomes

1. The researcher designed a working RFEIS.
2. The researcher designed and optimized RFEIS electrostatic discharge and combustion characteristics using finite element modeling. The researcher verified and further

optimized RFEIS electrostatic discharge and combustion characteristics through combustion test chamber testing.

3. The researcher demonstrated 15 hours durability in a hot firing test engine.
4. The researcher measured NOx emissions of 0.72 g/BHP-hr (at an equivalence of 0.6 in a single cylinder engine with lean air-fuel ratio), and of 0.51 g/BHP-hr (in a single cylinder engine with cooled exhaust gas recirculation (EGR) and stoichiometric air-fuel ratio, at 29.4 percent EGR).
5. The researcher demonstrated stable engine operation at 90 percent of the lean limit.
6. The researcher tested a standard ignition system in a single cylinder engine with a lean air-fuel ratio to compare with RFEIS. The RFEIS demonstrated lower lean limits and lower NOx than the standard ignition system, by 30 and 20 percent respectively.
7. The researcher verified that data generated from this research support the ignition system's projected capital cost of \$8 per kWe and life cycle cost of \$.25 per MWe-hr.

Conclusions

1. The researcher successfully proved the feasibility of RFEIS by designing and operating a working prototype.
2. The researcher has created accurate computer models.
3. While this objective was met, significantly longer endurance tests must be successfully completed.
4. The new ignition system is capable of igniting lean mixtures in an operating one-cylinder system with stable operation and low NOx formation. The RFEIS reduced NOx formation by 20 percent. The researcher did not complete mapping the operating envelope for NOX emissions. The project did meet the upper limit of the performance objective for NOx (0.51 g/BHP-hr). Significant work must be done to integrate this technology into a full engine that can meet or beat the California emission goals.
5. The achievement of this goal allows engine designers more flexibility in meeting the emissions goals.
6. The RFEIS demonstrated the ability to ignite leaner, more dilute mixtures with greater consistency than spark ignited systems.
7. While it is too early to predict cost accurately, it appears as though the researcher met this cost objective.

Recommendations

The program administrator recommends that the researcher run tests of the RFEIS on additional fuels, including methane and hydrogen. The researcher should complete mapping of NOX emissions as function of ignition timing, equivalence ratios and load transitions. In addition, the program administrator recommends that the researcher run extended durability tests, of weeks to months, using a wider variety of fuels likely used in distributed generation applications. The program administrator recommends that the researcher conduct fluid dynamic analysis of burn duration, swirl, and turbulence to determine optimum combustion chamber geometry.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow on funding within the PIER Program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit of this project is reduced environmental impacts of the electricity supply system in California. Reduced NOx emissions are real benefits the RFEIS offers to the state of California. In terms of distributed generation and based on data from the Energy Commission, none of the existing reciprocating engines can meet the Air Resources Board's (ARB) 2007 NOx emissions standard of 0.07 pounds per megawatt –hour (lb/MW-hr) (0.024 g/BHP-hr). However, an engine with the RFEIS, operating stoichiometric with EGR, and with a three-way catalyst could meet this standard, which translates into NOx emissions' reduction of 85 percent. At present, the ARB has not set such a low emissions level for any but the South Coast Air Quality District, but if this standard is expanded to other districts, further and widespread NOx emissions' reduction can be realized.

Additional and unanticipated benefits can be realized in truck application. In terms of heavy-duty truck engines, the 2007 emissions levels are also impossible to achieve with current diesel technology. The gasoline-fueled, cooled EGR technology with RFEIS will reduce NOx emissions from the current 2 g/BHP-hr for diesels to as low as the 0.015 g/BHP-hr demonstrated in the Advanced Reciprocating Internal Combustion Engines (ARICE) program, at the same horsepower level as the current diesel design. Initial cost savings is another important benefit. RFEIS allows a 25 percent upgrade in rating over standard ignition because of the extended knock limit with EGR, an advantage that will significantly reduce the initial cost of engines in both the industrial and transportation sectors.

2.22. Self-Optimizing Air Conditioner Controller

Awardee: Energy Savers International
Principal Investigator: T.S. (Jay) Jayadev

Introduction

Air conditioning is a major user of electricity in California. As communities in inland areas develop, air-conditioning use grows. While some research has focused on improving air conditioning hardware, this project was focused on control. Most residential air conditioners and heat pumps operate at a constant compressor/fan speed. If the compressor/fan speed on existing units could be varied based on overall energy performance, considerable energy might be saved. The researchers postulated savings of up to 20 percent of the energy used by an air conditioner.

Tracking the energy performance index (EPI) could permit the control system to operate an air conditioner at the best energy efficiency in real time. The researchers proposed to accomplish this by a serial approximation technique. The processor would collect data from the sensors, allow time for the system to come to steady state, and repeat this process every minute for five minutes. From these data the controller would calculate the EPI.

The microprocessor would decrement the indoor fan frequency starting at 60 hertz (Hz) in increments of 5 Hz and compare the new EPI with the old EPI. If the change in EPI was positive, decrementing would continue in the same direction until the change in EPI reversed sign. At that point, the direction of search would be reversed and the indoor fan frequency would be incremented at intervals of 2.5 Hz until the sign changed again, thereby identifying the peak. The controller would register the optimum and continue to operate at that frequency.

Objectives

The goal of this project was to prove the feasibility of an on-site optimizing controller concept that could increase energy efficiency of existing air conditioners and heat pumps by 20 percent. The efficiency gain was to be achieved by operating single speed PCS compressor/fan motors at variable speeds. The researchers established the following project objectives:

1. Demonstrate that the proposed air-conditioner controller can be used to retrofit existing residential air-conditioning systems containing single speed permanent split capacitor (PSC) compressor and fan/blower motors.
2. Demonstrate that the proposed air conditioner controller is capable of driving the fan motors and compressor motor at different frequencies at the same time.
3. Demonstrate that the proposed controller is capable of operating the compressor at two speeds (60 Hz and 30 Hz).
4. Demonstrate that the proposed controller is capable of operating the PSC motor fan/blower with continuous variation in speed between 25 Hz to 65 Hz.

5. Demonstrate that the proposed self-optimizing controller is capable of accurately calculating, in real time, the Energy Performance Index (EPI) from three to four air temperature sensors and one power sensor.
6. Confirm that the control logic based on EPI is capable of achieving the optimal coefficient of performance within plus/minus 3 percent.
7. Demonstrate that the proposed controller is capable of improving the energy efficiency of a single-phase, single-speed 3-ton air conditioner with PCS motors by at least 20 percent in a retrofit configuration.
8. Confirm from the research findings that the projected manufacturing cost of \$90 and installation cost of \$30 for the proposed controller can be supported.

Outcomes

1. A modified controller was retrofitted into a commercially available air conditioner. It successfully operated the machine.
2. The controller operated the compressor motor and compressor and evaporator fans at different frequencies at the same time.
3. Although not specifically discussed, the final report inferred that the controller operated the compressor at 60 Hz and 30 Hz.
4. The final report indicated this objective was met. However it presented no details.
5. The processor recorded the readings of total power, indoor and outdoor airflows, and input and output temperatures of these airflows. The controller identified the optimum fan speed using the embedded logic and continued to operate in that condition.
6. The researchers found the original concept for an Energy Performance Index (EPI) used for real-time optimization was not effective. Both computer simulations and experiments demonstrated the original EPI predicted that the optimal fan speed was the maximum fan speed, whereas an intermediate fan speed normally produced the highest efficiency. The researchers developed an alternative EPI called "EER_{reject}," which is the ratio of heat transfer rate out of the condenser divided by total power consumption. The new EPI proved to be highly effective. The speed that maximized EER_{reject} also maximized total efficiency. The researchers also found a benefit to varying the condenser fan speed, not just the evaporator fan speed. The benefit was negligible at high compressor speed, but was significant at low compressor speed.
7. The new controller reduced energy use by 18.1 percent on a 2.5 ton Frigidaire air conditioner.
8. Enalasys (a company) estimated production costs (10,000 quantity lots) at approximately \$70 with an estimated cost to install of \$30 to \$35.

Conclusions

1. This objective was met.
2. This objective was met.
3. This objective was met.

4. This objective was met.
5. The researchers were able to optimize performance with a minimum number of relatively inexpensive sensors.
6. The researchers improved on the metric used to optimize performance.
7. An 18 percent improvement in energy consumption is impressive. Before additional product refinement is performed, the researchers should test the controller on various brands and sizes of air conditioners to see the range of savings possible. The final report presented little data to allow for independent verification of the result. The researchers should submit actual data to a qualified third party to ensure that their conclusions are sound.
8. While the researchers met the goal for production cost, they did not estimate the price to the consumer. Markups to cover selling, general and administrative expense (SG&A) costs and profit may greatly increase the price to the consumer. Also, most technicians will not make a house call and charge for only one-half an hour. If they charged for an entire hour, the cost of labor to install would double. The researchers did not present their methodology for determining payback to the consumer. Pricing and payback should be reviewed in greater detail.

Recommendations

Because the addition of a new controller is a major modification to an expensive home appliance, the researchers should consider partnering with an air conditioner manufacturer to evaluate any long-term reliability issues. Two other issues to consider are warranty and field service. Warranties may be voided with the addition of a new controller and field service may be difficult to obtain once the factory unit has been modified. The researchers should reevaluate the business model that is based on independent retrofits. One alternative is to engage the manufacturers in providing “factory upgrades.”

Since this project was completed, manufacturers have announced great advancements in air conditioner control and motors. A thorough review of the current state of the art should be conducted before any additional work on the proposed concept begins.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for subsequent funding within the PIER Program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.

- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. If the self-optimizing controller were used in all existing residential air conditioners in California, ratepayers could save up to \$400 million per year in energy costs. Along with the cost savings would be a reduction in site electrical energy use of more than 4,000 gigawatt-hours, and a reduction in emissions of carbon dioxide, nitrogen oxide, and sulfur dioxide of 11,300, 400, and 735 thousand pounds per year, respectively. The payback period for a residence with a 2.5 ton air conditioner located in an inland region of California could be as low as 2.1 years.

2.23. New Powerline Control Technology for Lighting and Heating, Ventilation and Air Conditioning

Awardee: Powerline Control Systems
 Principal Investigator: Marshall Lester

Introduction

Power systems in existing, electrically complex buildings, such as commercial, industrial, and institutional facilities, could save energy if they were fitted out to intercommunicate with individual load-control devices. In new construction, cost-effective control circuits can be incorporated into the original wiring. The cost of additional hardwiring for an energy-management system (EMS) in existing buildings is generally prohibitive. Typical solutions that utilize either existing building electrical wiring or wireless communications have been costly, or unable to function accurately in an electrically complex environment. The development of a cost-effective, reliable communications system for existing buildings would produce energy savings.

The environmental benefits and associated cost-effectiveness of reducing energy usage with EMS in new commercial and industrial environments are well established. Assuming the communications problem can be solved for existing buildings, retrofitting them should produce similar benefits. As an example, if the retrofit enabled only savings in lighting (assumed to represent 30 percent of the building's total load), a typical reduction in energy for lighting of 20 to 45 percent from an energy management system would yield an overall building energy savings of 6 to 13 percent. Given the California Energy Commission's estimate that the commercial and industrial sectors accounted for over half of total electricity consumption in California between 1990 and 2001, the potential energy savings from such retrofits could be substantial.

The researcher demonstrated that it is feasible to provide highly reliable communications through existing building wiring in electrically complex (3-phase, 120/208-volt and 277/480-volt)

environments. This was done by using modules developed and built for the project to send and receive a series of precisely timed and relatively large (tens of volts) electrical pulses superimposed on top of the standard alternating current (AC) power sine wave over the AC line. One pulse per half-cycle of the AC sine wave is sent in a time position that is relative to its data value. The position corresponds to a value of 0, 1, 2, or 3 (a Pulse Position Modulation scheme.)

Objectives

The goal of this project was to determine the feasibility of technology to provide highly reliable and low-cost communications suitable for EMS control of lighting and heating, ventilation and air conditioning (HVAC) over existing electrical circuits in electrically complex commercial, industrial, and institutional buildings. The researchers established the following project objectives:

1. Fabricate at least 20 wired-in, powerline, communication-analysis modules designed to capture the data required to assess the feasibility of utilizing this technology in the targeted electrical environments.
2. Place the analysis modules in a variety of locations (10-20 buildings) that are representative of the target environment, and capture the noise, signal level, and communications reliability data for a statistically valid sample.
3. Demonstrate that the technology communicates with a reliability level of at least 99 percent in the targeted electrical environments and in a manner transparent to connected electrical/electronic equipment.
4. Show that the communication efficiency target can be attained with two-way transmission/receiving circuitry that is in the projected cost range of \$3 to \$5 per communication node.

Outcomes

1. Twenty four 120/208 volt (V) and twenty four 277/480 V powerline communication analysis modules were fabricated. The hardware and firmware required for these modules were also developed. In addition, three 120/208 V and two 277/480 V three-phase powerline interface devices were created, along with the necessary data-acquisition and recording software.
2. Analysis modules were placed at 15 random test locations on the California State University Northridge campus. Test data was collected 4 times every 30 minutes for one week, and the associated level and number of retry attempts was logged. The table below summarizes the locations and characteristics of the 15 test locations: Test Locations for Energy-Management System Trials

Table 7. Test locations for energy management trials

Location	Equipment
CSUN Electric Shop	Repair Equipment, offices, fluorescent lighting
CSUN Rm. 160	High bay multi-ballast fluorescent lighting
CSUN Receiving	Warehousing, offices, fluorescent lighting, battery chargers
CSUN Parking Structure	HD Lighting fixtures
CSUN PPM Offices	Florescent lights, office equipment
High Quality	PCB production machines
Prototype Sheet Metal	Metal working machines, offices
All Sale Electric	Warehousing, offices, fluorescent lighting
CSUN Post Office	Warehousing, offices, fluorescent lighting
CSUN Receiving	Warehousing, offices, fluorescent lighting
CSUN Electric Shop	Repair equipment, offices, fluorescent lighting
CTL Emergency Lighting	Production machinery, offices, fluorescent lighting
CSUN Physical Plant	Chillers, heaters, boilers, HID lighting, pumps, motors
PCS Warehouse	Production machinery, offices, fluorescent lighting
Sysco Foods	Chargers, refrigeration equipment, HID lighting, offices

Reliability, noise, signal-level, and communications-reliability data were collected. Signal-level and communications-reliability data are presented in the final report. The final report does not present the noise data; however, it does represent that "...the signal strength at the receiver is generally much greater than the strength of any noise that is on the powerline."

3. Overall communications reliability for the 15 test sites was 98.9 percent for the first attempt, increasing to 99.7 percent for the second, further increasing to 99.8 percent for the third, and achieving 99.9 percent after the fourth. These results indicate the importance of a retry or multiple transmission mechanism in the communication protocol.

The existing electrical/electronic equipment at each location was monitored for proper operation during testing, to determine whether any interference was caused by the communication technology. No evidence of problems was noted.

4. No cost data was presented in the report, leaving no basis to support researcher's original proposition, that reliable, two-way communication can be achieved for a cost of \$3 to \$5 per communication node.

Conclusions

1. The researcher's powerline, communications-analysis modules, powerline interface modules, and associated hardware, firmware, and data-acquisition and recording software were developed and fabricated as proposed.
2. The locations and associated electrical/electronic equipment used for the test provided a reasonable sample of typical, small-to-medium-scale processes that may interact with or be impacted by a communications protocol.

3. The test data confirmed that this method of communication can provide greater than 99 percent communications reliability under field test conditions for at least one week (overall reliability was 99.9 percent). There was no observed interference with any of the electrical/electronic equipment in the test locations, although it is not clear whether examples of especially sensitive electronic devices requiring very high power quality were present in the test sites.
4. Cost for this technology is at least as important as its communications reliability. Without cost data in the report, it is not possible to assess this or compare it to other competing communications technologies.

In summary, the researcher demonstrated that it is feasible to provide highly reliable data communications through existing building wiring in electrically complex (3 phase, 120/208-V and 277/480-V) non-residential environments in a manner that does not interfere with typical connected equipment.

Recommendations

Additional research should be conducted in the following areas:

1. The objective of demonstrating the ability to provide communications at a cost of \$3 to \$5 per module was not addressed in the final report. It is important to test this premise, since one of the technology's potential competitive advantages is its combination of high communications reliability with low cost.
2. Evaluate the technology's ability to communicate between multiple sub-panels, which is a common configuration in commercial/industrial applications.
3. Develop interfaces to recognized EMS devices, and test operation of the technology in a representative number of operating EMS systems.
4. Explore noise/interference potential in more detail and establish whether there are power-quality impacts for a wider range of installed equipment.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow-on funding within the PIER Program.

Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.

- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research would be increased affordability of electricity in California. This would occur through a reduction in the energy used by commercial/industrial buildings, with corresponding savings in energy costs that would potentially flow through to customers of the enterprises utilizing these buildings. This conclusion depends on successfully bringing this concept to market in a product that delivers the communications reliability found in this research, at a price that helps make the EMS system cost-effective in existing buildings.

2.24. A Novel Integrated Doubly-Fed Electric Alternator/Active Filter for Wind Power Applications

Awardee: Texas A&M University
 Principal Investigator: Hamid Toliyat

Introduction

Wind energy ranks as one of the most promising renewable energy resources. Its role in solving the worldwide energy crisis is limited by the intermittent nature of wind itself. Existing turbines and other devices that convert wind into electrical power are constrained in performance by quality issues that include voltage, voltage frequency, and harmonic stability. Problems of harmonic stability may originate either with the wind-turbine generator or within the utility grid. Wind operators normally install expensive add-on equipment to overcome these performance limitations.

The primary benefits to the ratepayer from this research include improved performance and design simplicity coupled with lower costs for wind-turbine generators. This will help to reduce environmental impacts of the California electrical supply system by increasing the amount of cost-effective wind generation substituting for fossil generation. Simultaneously, it will improve power quality and impacts on the electrical transmission system. Poor power factors that cause energy losses in large rotating equipment at customer sites would also decrease by an unquantified but significant amount.

The researcher evaluated a new approach for winding a generator and integrating an electronic filter that avoids costly add-on equipment to control power quality. The researcher has named this concept the Integrated Doubly-fed Electric Alternator/Active (IDEA) filter. The researcher claimed it capable of simultaneously capturing maximum power from the wind and improving power quality. The latter is achieved by canceling the most significant and troublesome harmonics of the utility grid and providing power factor correction and reactive power compensation to the grid.

The proposed method allows decoupled control of the active and reactive powers and harmonic compensation. Current sensors sample the nonlinear load current, and then a band rejection filter removes the fundamental current. A stator flux field oriented control monitors the doubly

fed induction generator (DFIG). Decoupled control of the active and reactive powers and harmonic compensation is achieved and suitable current is generated to supply the rotor circuit. In this system the rotor-side power converter controls the proper excitation of the system, while the front-end power converter allows the bi-directional power flow in the rotor circuitry and operation at subsynchronous speed and supersynchronous speed modes. Each of the two feeds to the generator feed cancels distortions in power quality from the other feed.

Project Objectives

The goal of this project was to prove the feasibility of incorporating an integrated, doubly-fed, alternator/active filter on a variable-speed wind turbine to capture maximum power and improve power quality at lower cost. The researcher proposed the following objectives:

1. Confirm that the mathematical model of the concept developed in this project is capable of supporting accurate computer simulations.
2. Demonstrate with computer simulations that the developed system, when integrated into a grid-connected wind-energy system, will maintain grid power factor 0.99, plus/minus 0.5 percent, while maintaining total harmonic distortion (THD) below 5 percent.
3. Demonstrate that the prototype 5.6 kilowatt (kW) simulated wind turbine with the developed system incorporated is capable of achieving maximum power density, while maintaining power factor at 0.99, plus/minus 0.5 percent and THD below 5 percent. These objectives will be met under various wind speeds.
4. Identify the optimal operating points for cost-effective operation of the overall system through prototype testing.
5. Validate from the research findings that the projected 10 percent reduction in the capital cost of a variable-speed wind turbine that employs the proposed technology continues to be supported as compared to a state-of-the-art wind-turbine system that incorporates a separate, active filter.

Outcomes

This project achieved the following outcomes:

1. The researcher developed the mathematical model of the overall system in the Matlab/Simulink calculational environment. He later simulated this detailed model on a digital computer.
2. The simulation model accurately predicted the performance of the system over the wind-speed conditions simulated. The researcher simulated changes in wind speed from 8 to 12 meters per second. Modeling changing wind speed is important to simulate wind intermittency. The researcher also modeled the system with and without harmonic distortion. The researcher demonstrated that once the system is integrated into an electric grid, the power factor could be corrected to 0.99, plus/minus 0.5 percent. He studied only a single non-linear load to represent the utility grid and customer load.

3. The simulated, integrated wind generator and active filter produced maximum power density by maintaining vector-controlled operation with 0.99, plus/minus 0.5 percent power factor and less than 4 percent total harmonic distortion (THD).
4. The researcher determined the optimal operating control set points for cost-effective application of the overall system on a laboratory setup. These optimal operating control set points were determined for each of the various wind speeds and loading conditions simulated in seven case studies. The researcher simulated wind speeds of 8 to 12 meters per second.
5. The fabricated, integrated alternator and active filter for wind-power applications could reduce the capital cost by about 10 percent for combined generation of electric power and filtering the utility-line harmonics. Avoiding the need for add-on harmonics filtering equipment provides the cost reduction.

Conclusions

This project addressed the problems of power quality and cost for wind electrical generation. The researcher proposed an integrated, doubly-fed, electric alternator/active filter for wind-energy conversion systems connected to a power grid. The developed system demonstrated capability to capture the maximum energy from fluctuating winds while controlling important features of power quality. In this project:

1. The researcher developed an electric-field-oriented control method to control the rotor-side, current-regulated power converter for dynamic excitation of the rotor circuitry within the induction generator. This method controls both fundamental current and harmonic currents. The researcher demonstrated the capability of the control strategy to control the generated active and reactive power and, independently, the amount of harmonic compensation in the grid.
2. The researcher developed a sensor-less method to determine rotor position for the rotor-side converter. The researcher compared the performances of systems with and without position sensors. He also observed perfect rotor position estimation over a wide range of speed conditions. The most important wind-speed conditions evaluated included step changes in wind speed (wind fluctuations) and subsynchronous and supersynchronous rotor conditions (active and reactive power conditions).
3. The front-end converter controls the power flow between the direct current (DC) bus and the alternating current (AC) side and allows the system to be operated in subsynchronous and supersynchronous speed. The generated harmonics compensate for the harmonic currents needed by the non-linear load. This method removed the simulated harmonics currents of the utility grid.
4. Laboratory experimental results proved the effectiveness of the proposed method. The researcher demonstrated that the developed system, integrated into an electric grid, could correct the power factor to 0.99, plus/minus 0.5 percent.
5. The project proved the feasibility of the concept of controlling generated active and reactive power, as well as compensating for harmonics from the grid. A non-linear load

was provided harmonic-free power in tests. The project successfully demonstrated the concept as capable of providing increased power extraction, while maintaining power quality compared to current wind turbines.

Lower cost and improved performance of wind-turbine systems should enable greater use of wind generation at lower cost without threatening the high quality of power needed by utility customers. Avoiding the use of add-on active filters and compensating devices should also increase the overall reliability of wind-turbine generators. Expected cost reductions stem both from increased power extraction and the avoided cost of add-on filters. Add-on filters increase the cost of wind turbine-generator installations by at least 10 percent, and the percentage increases for smaller units. The program administrator considers the IDEA system inherently more reliable than conventional systems because the IDEA system has fewer components that could fail.

Recommendations

Recommended next steps include simulation and testing of multiple non-linear loads in the context of both strong and stiff networks and in “weak” grids. These further tests would use the system on an actual wind turbine generator. Further power-generation and harmonic-cancellation studies performed on an actual wind turbine will help generator manufacturers with increased efficiency and cost reduction of the developed system

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow-on funding within the PIER Program.

Receiving follow-on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and developments are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the California ratepayer from this research is reduced environmental impacts of the California electricity supply. This is accomplished by improved performance and design simplicity coupled with lower costs for wind-energy generation. Once implemented, this innovation could increase the amount of cost-effective wind generation substituting for carbon-based generation. Other benefits include the improvement of power quality and the reduction

of impacts on the electrical transmission system due to wind generation. Compared to existing wind-generation technology, approximately 3,300 megawatts (MW) could be installed in California at the same cost as 3,000 MW if the IDEA system was used. Energy losses in large rotating equipment at customer sites caused by poor power factors would also decrease by an un-quantified but potentially significant amount. Operational disruptions at facilities dependent on digital controls could be reduced as power quality is improved as well.

Considering that the total wind power generated in California is about 1,800 MW, it is possible that about 180,000 kilovolt amperes (kVA) of unsafe harmonic power also is generated. This accounts for about 10 percent harmonic power generated by each wind turbine. Generating one kVA of harmonic power may cost electricity users about \$100 per year. Reducing harmonic power using the developed technology could save customers about \$18 million per year. The exact saving could be much greater due to the fact that unwanted harmonics in the utility grid cause shutdowns and stoppages to end users sensitive to harmonics, especially those with digital controls and equipment.

2.25. Nanostructured Electrodes for Proton Exchange Membrane Fuel Cells

Awardee: University of California, Riverside
Principal Investigator: Yushan Yan

Introduction

Natural gas-based generation is an important source of electricity within California and elsewhere. Natural gas-based thermal power plants are much cleaner than coal or oil-based generation, but their pollutant emissions such as nitrogen oxides (NO_x) and carbon dioxide (CO₂) are still of concern because of increasingly stringent air quality regulations and concerns about global warming in California. As a result, environmentally preferred advanced generation technologies that are intrinsically more efficient and clean, with significant reduction in NO_x and CO₂ emissions, have been widely sought. Studies have shown that proton exchange membrane fuel cell (PEMFC) systems are attractive, especially for residential applications, because they are highly efficient even at the relatively small power levels suitable for residential applications, and they are capable of following the load swings typical in residential applications. PEMFC can significantly reduce primary energy consumption and pollutant emissions. Fuel cell power in a distributed generation applications also improves the reliability and quality of electricity supply and delivery.

However, the current proton exchange membrane (PEM) fuel cell systems have to overcome significant technology roadblocks before it becomes economically viable. For example, the current PEMFC uses platinum (Pt) or Pt alloy supported on carbon black particles as the catalyst. Current designs have very low Pt utilization rate (e.g., 20 to 30 percent). Platinum is expensive, trading above \$1,200 per ounce at the time of this writing. Low utilization of the Pt

translates into extremely high cost. Utilization rates are a function of surface area to weight ratios for the Pt catalyst.

The researchers have proposed an innovative approach to increase Pt utilization rates using carbon nanotube catalyst supports. By reducing the particle size, the ratio of surface area to weight is increased, which should result in increased utilization and reduced precious metal (platinum) requirements. The Pt catalyst is supported on extremely small diameter carbon nanotubes.

Objectives

The goal of this project was to determine the feasibility of using a nanostructured electrode design to reduce the overall precious metal catalysts requirements. The researchers established the following project objectives:

1. Demonstrate that multi-wall carbon nanotube (MWNT) arrays with uniform diameter and with vertical alignment to the carbon fiber surface can be produced by catalyzed chemical vapor deposition on carbon paper or carbon cloth.
2. Demonstrate that catalyst nanoparticles (Pt) on the surface of carbon nanotubes (CNT) can be deposited through electrodeposition. The targeted loading is 20 to 30 percent of the current ink process.
3. Generate triple-phase-boundary in the catalyst layer by impregnation of polymer electrolyte, development of membrane electrode array (MEA) and a single cell.
4. Demonstrate that the potential for cost saving for the proposed fuel cell versus the conventional PEM fuel cell is 10 to 30 percent based on the savings from reduced Pt use.

Outcomes

1. The researchers successfully grew MWNTs on carbon paper through a direct chemical vapor deposition (CVD) process using electrodeposited cobalt (Co) as the catalyst for MWNT growth. The researchers also used mesoporous silica as a sacrificial layer for the production of aligned CNTs. The researchers abandoned this effort after finding that the non-aligned CNTs performed well, and the introduction of a sacrificial layer would increase the complexity of the manufacturing process.
2. The project demonstrated successful deposition of Pt on the carbon substrate. The researchers developed an oxidation method with a mixture of acids (e.g., sulfuric and nitric acid) to functionalize the CNTs before electrodeposition and in-situ reduction. Following the functionalization step, the researchers successfully deposited Pt nanoparticles on CNTs by electro-deposition and in-situ reduction. The in situ reduction produced Pt nanoparticles of near 5 nanometers (nm) diameter while electro-deposition produced 25 nm Pt particles. This increases the effective surface area by 27 times.
3. The researchers fabricated single cells and tested the MEAs. Compared with conventional electrodes, improved polarization behavior was observed for the CNT based electrode. In activation controlled regions of the cell, the measured current density for CNT-based electrode is higher than that of the conventional electrode (e.g., 153 millampere per square centimeter (mA/cm^2) vs 98 mA/cm^2 at potential of 0.8 V). This means that the CNT based electrode has higher activity towards oxygen reduction, an

important characteristic for fuel cell application. In addition higher active surface area due to the improved Pt utilization, the enhanced activity may also be attributed to the unique structure of CNT.

4. The researchers demonstrated a 50 percent increase in Pt utilization, versus the target of 10 to 30 percent.

Conclusions

The researchers successfully demonstrated the feasibility of carbon nanotube based electrode catalyst to increase the utilization rate of Pt in the electrodes of proton exchange membrane (PEM) fuel cells. They demonstrated that, by using in situ-reduction, the Pt utilization increases from 30 percent in the conventional electrode to 60 percent in the carbon nanotube based electrodes. Further improvements are possible. The researchers found that alignment of the CNT did not appreciably improve utilization rates and would add manufacturing complexity.

Recommendations

Future research should include development of complete fuel cell stacks and performance and durability testing, especially with respect to the adhesion of Pt catalysts particles on the CNT. In addition, safety issues need to be specifically addressed given the possibility of the deposition catalyst (Co) providing a short circuit in application. The impact and importance of Pt catalyst particle surface roughness should be investigated as surface roughness may further increase area and catalyst activity. The researcher, working with a fuel cell manufacturer, should estimate the capital and operating costs of a fuel cell using this technology. Increased Pt loading to improve overall efficiency of PEMs should be investigated to determine capital cost tradeoffs.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER Program, the program administrator has determined that the proposed technology should be considered for follow on funding within the PIER Program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is reduced environmental impact of the California electricity supply and transmission system. PEM fuel cells have significantly lower emissions than natural gas-fired, combined cycle power plants. Because they are so clean, PEM fuel cells could be located throughout cities reducing or eliminating the need for new

transmission lines. It is still not clear that PEM fuel cells using this technology will cost less than a large combined cycle power plant with exhaust cleanup devices, but this project moves the cost in the right direction. Fuel utilization, while not currently as high as that on large combined cycle power plants, benefits from the lack of transmission losses when PEM fuel cells are installed locally. Application of this technology may improve the overall fuel utilization of PEMs. Fuel cells using this technology and applied in residential applications or dispersed commercial applications would also provide increased electric system reliability.

Estimating the potential market, and consequently actual benefits, for this technology is speculative. However, 15,000 to 30,000 megawatts (MW) of landfill and digester gas, and gasified biomass could be developed with fuel cells. Some fraction of these fuel cells could use this technology. Further, the existing 45,000 MW of existing fossil-fueled capacity in California represents an order of magnitude estimate of the maximum potential market. Solid oxide fuel cells would likely be the choice for the majority of fuel cell base load, while PEM fuel cells would be the probable choice for distributed power generation with variable load. It will likely take 7 to 10 years, or more, of development and commercialization before this technology begins to provide significant benefit to California.

Glossary of Terms

AC	Alternating current
ARB	Air Resources Board
ARICE	Advanced reciprocating internal combustion engines
ASP	Activated sludge process
ATP	Alternate Transients Program
Btus	British thermal units
CBR	Case base reasoning
CFD	Computational fluid dynamic
CMF	Corrosion mitigation facility
CMS	Carbon molecular sieve
CNT	Carbon nanotubes
CVD	Chemical vapor deposition
DC	Direct current
DFIG	Doubly fed induction generator
DG	Distributed generation
DO	Dissolved oxygen
DOE	Department of Energy
DSP	Digital signal processor
DSS	Dry steam scrubbing
EGR	Exhaust gas recirculation
EISG	Energy Innovations Small Grants
EMS	Energy management systems
EPI	Energy performance index
g/bhp-hr	Grams per brake horsepower-hour
GW	Gigawatts
GWh	Gigawatt hours
HCCI	Homogenous charge compression ignition
HP	Horsepower
HTL	Hole-transporting Layer
HVAC	Heating, ventilation, air conditioning
Hz	Hertz
IAR	Independent assessment reports
IC	Internal combustion
IDEA	Integrated doubly-fed electric alternator/active
IEEE	Institute of Electrical and Electronics Engineers
ISOFC	Integrated solid oxide fuel cell
kVA	Kilovolt amperes
KWe	Kilowatt-electric
LF	Load flow
LFGTE	Landfill gas to electricity
MAIFI	Momentary Average Interruption Frequency Index

MATLAB	A software engineering toolbox for mathematical modeling
MEA	Membrane electrode array
MGD	Million gallons per day
MM-CMSM	Mixed matrix carbon molecular sieve membranes
MM-PM	Mixed matrix polymer membranes
MPa	Megapascals
MW	Megawatts
MWe-hr	Megawatt electric-hour
MWNT	Multi-wall nanotubes
NG	Natural gas
Nm	Nanometer
OCC	One-cycle control
OCM	Oxidative coupling of methane
OPV	Organic photovoltaic
PAS	Photoacoustic sensor
PAS	Photoacoustic spectroscopy
PCS	Permanent split capacitor
PEI	Polyetherimide
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
PFC	Power factor correction
PID	Proportional-integral-derivative
PIER	Public Interest Energy Research
PLC	Powerline communication
PPM	Parts per million
PPMVD	Parts per million volumetric dry
PSCAD/EMTDC	Power systems computer aided design/ElectroMagnetic Transients for direct current
PSZ	Partially stabilized zirconia
PV	Photovoltaic
QC	Quantum cascade
RD&D	Research, development and demonstration
RFEIS	Radio frequency electrostatic ignition system
RH	Relative humidity
Rpm	Revolutions per minute
SAIDI	System average interruption duration index
SAIFI	System average interruption frequency index
SEER	Seasonal energy efficiency ratio
SGA	Selling, general and administrative
SOFC	Solid oxide fuel cell
SPR	Static pressure reset
TEM	Transmission electron microscopy
THD	Total harmonic distortion
UG	Underground

UPQC	Unified power quality conditioner
VAV	Variable air volume
VFD	Variable frequency drives
W _p	Watt peak
YZA	Yttria zirconia